



SORGHUM AND MILLETS

in human nutrition

On the left, there are two illustrations: one of three millet plants with their characteristic panicle heads, and another of a woman in a headscarf sitting cross-legged, feeding a small child from a bowl.

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Preface

For millions of people in the semi-arid tropics of Asia and Africa, sorghum and millets are the most important staple foods. These crops sustain the lives of the poorest rural people and will continue to do so in the foreseeable future. Sorghum and millets grow in harsh environments where other crops do not grow well. Improvements in production, availability, storage, utilization and consumption of these food crops will significantly contribute to the household food security and nutrition of the inhabitants of these areas.

Sorghum and millets in human nutrition is a new addition to the FAO Food and Nutrition Series. The publication is broad in scope and coverage, starting with the history and nature of sorghum and millets and dealing with production, utilization and consumption. It provides extensive information on the nutritional value, chemical composition, storage and processing of these foods. In addition, the antinutritional factors present in these foods and ways of reducing their health hazards are discussed. The authors have described formulations of various popular foods prepared from sorghum and millets and their nutritional composition and quality, and they have compiled many recipes for the preparation of foods from regions where sorghum and millets are important dietary staples. An extensive bibliography is included as well.

Readers of this book may also be interested in the standards for sorghum and pearl millet grains and flours

prepared by the Codex Alimentarius Commission under the Joint FAO/WHO Food Standards Programme.¹

FAO appreciates the collaboration and assistance of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in the preparation of this book. The Organization acknowledges the contributions of Dr R. Jambunathan and Dr V. Subramanian, both of ICRISAT, to Chapters 1, 2, 3 and 5 as well as those of Dr Y.G. Deosthale, of the National Institute of India, to Chapters 1, 4 and 6 and the Annex.

Sorghum and millets in human nutrition is intended to provide up-to-date scientific and practical information to scientists, government officials, extension workers, university professors and others interested in these foods. It is hoped that this text will assist them in the development of training programmes for their staff and students.

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¹Codex Alimentarius Commission, 1990. *Codex standards for cereals, pulses, legumes and derived products*. Supplement 1 to Codex Alimentarius Vol. XVIII. Rome, FAO/WHO. 33 pp.

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Chapter 1

Introduction

Sorghum and millets have been important staples in the semi-arid tropics of Asia and Africa for centuries. These crops are still the principal sources of energy, protein, vitamins and minerals for millions of the poorest people in these regions.

Sorghum and millets are grown in harsh environments where other crops grow or yield poorly. They are grown with limited water resources and usually without application of any fertilizers or other inputs by a multitude of smallholder farmers in many countries. Therefore, and because they are mostly consumed by disadvantaged groups, they are often referred to as "coarse grain" or "poor people's crops". They are not usually traded in the international markets or even in local markets in many countries. The farmers seldom, therefore, have an assured market in the event of surplus production.

The cereals considered in this publication include sorghum, pearl millet, finger millet, foxtail millet, common millet, little millet, barnyard millet and kodo millet (Table 1). Teff (*Eragrostis tef*), which is extensively cultivated in Ethiopia, is not strictly a millet and is therefore not included. Other millets such as fonio (*Digitaria exilis*) and Job's tears (*Coix lacryma-jobi*) are of minor importance and are not described here.

SORGHUM

Sorghum, *Sorghum bicolor* (L.) Moench, is known under a variety of names: great millet and guinea corn in West Africa, kafir corn in South Africa, *dura* in Sudan, *mtama* in eastern Africa, *jowar* in India and *kaoliang* in China (Purseglove, 1972). In the United States it is usually referred to as milo or milo-maize (Table 1). Sorghum belongs to the tribe Andropogonae of the grass family Poaceae. Sugar cane, *Saccharum officinarum*, is a member of

TABLE 1

Origins and common names of sorghum and millets

Crop	Common names	Suggested origin
<i>Sorghum bicolor</i>	Sorghum, great millet, guinea corn, kafir corn, <i>dura</i> , <i>mtama</i> , <i>jowar</i> , <i>cholam</i> , <i>kaoliang</i> , milo, milo-maize	Northeast quadrant of Africa (Ethiopia-Sudan border)
<i>Pennisetum glaucum</i>	Pearl millet, <i>cumbu</i> , spiked millet, <i>bajra</i> , bulrush millet, candle millet, dark millet	Tropical West Africa
<i>Eleusine coracana</i>	Finger millet, African millet, koracana, <i>ragi</i> , <i>wimbi</i> , <i>bulo</i> , <i>telebun</i>	Uganda or neighbouring region
<i>Setaria italica</i>	Foxtail millet, Italian millet, German millet, Hungarian millet, Siberian millet	Eastern Asia (China)
<i>Panicum miliaceum</i>	Proso millet, common millet, hog millet, broom-corn millet, Russian millet, brown corn	Central and eastern Asia
<i>Panicum sumatrense</i>	Little millet	Southeast Asia
<i>Echinochloa crus-galli</i>	Barnyard millet, <i>sawa</i> millet, Japanese barnyard millet	Japan
<i>Paspalum scrobiculatum</i>	Kodo millet	India

this tribe and a close relative of sorghum. The genus *Sorghum* is characterized by spikelets borne in pairs. Sorghum is treated as an annual, although it is a perennial grass and in the tropics it can be harvested many times.

In 1753 Linnaeus described in his *Species plantarum* three species of cultivated sorghum: *Holcus sorghum*, *Holcus saccatus* and *Holcus bicolor*. In 1794 Moench distinguished the genus *Sorghum* from the genus *Holcus*, and in 1805 Person suggested the name *Sorghum vulgare* for *Holcus sorghum* (L.). In 1961 Clayton proposed the name *Sorghum bicolor* (L.) Moench as the correct name for cultivated sorghum and this is currently being used.

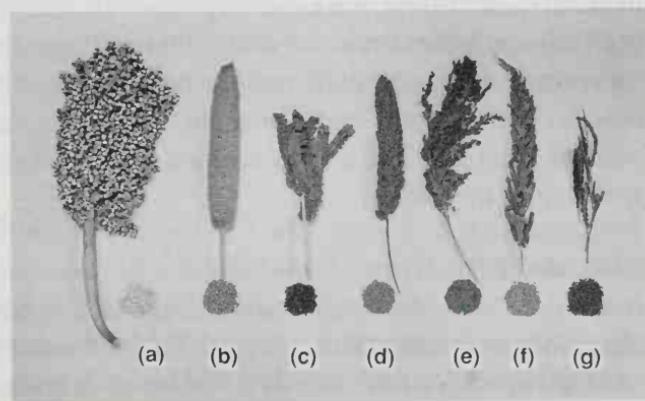
The classification of sorghum by Snowden (1936) is detailed and complete. Other classifications proposed since that time have been modifications or adaptations of the Snowden system. Harlan and de Wet (1972) published a simplified classification of sorghum which has been checked against 10 000 head samples. They divided cultivated sorghum into five basic groups or races: bicolor, guinea, caudatum, kafir and durra. The wild

type and shatter cane are considered two other spikelet types of *S. bicolor*. A study of polymorphism of 11 enzymes permitted classification of sorghum into three enzymatic groups. The first includes mainly guinea varieties of West Africa; the second southern African varieties of all five races; and the third durra and caudatum types of Central and East Africa (Ollitrault, Escutte and Noyer, 1989).

The cultivated sorghum of the present arose from a wild progenitor belonging to the subspecies *verticilliflorum*. The greatest variation in the genus *Sorghum* is observed in the region of the northeast quadrant of Africa comprising Ethiopia, the Sudan and East Africa (Doggett, 1988). It appears that sorghum moved into eastern Africa from Ethiopia around 200 AD or earlier. It was adopted and carried to the savannah countries of eastern and southern Africa by the Bantu people, who used the grain mainly to make beer. The Bantu people probably began their expansion from the region of southern Cameroon about the first century AD, moved along the southern border of the Congo forest belt and reached eastern Africa possibly before 500 AD. The present-day sorghums of central and southern Africa are closely related to those of the United Republic of Tanzania and more distantly related to those of West Africa, as the equatorial forests were an effective barrier to this spread.

Sorghum was probably taken to India from eastern Africa during the first millennium BC. It is reported to have existed there around 1000 BC.

- (a) *Sorghum bicolor*,
- (b) *Pennisetum glaucum*, (c) *Eleusine coracana*, (d) *Setaria italica*, (e) *Panicum sumatrense*,
- (f) *Echinochloa* sp.,
- (g) *Paspalum scrobiculatum*



Sorghum was probably taken in ships as food in the first instance; dhow traffic has operated for some 3 000 years between East Africa (the Azanean Coast) and India via the Sebaean Lane in southern Arabia. The sorghums of India are related to those of northeastern Africa and the coast between Cape Guardafui and Mozambique.

The spread along the coast of Southeast Asia and around China may have taken place about the beginning of the Christian era, but it is also possible that sorghum arrived much earlier in China via the silk trade routes.

Grain sorghum appears to have arrived in America as "guinea corn" from West Africa with the slave traders about the middle of the nineteenth century. Although sorghum arrived in Latin America through the slave trade and by navigators plying the Europe-Africa-Latin America trade route in the sixteenth century, the crop did not become important until the present century. The case is similar for Australia.

Grain sorghum grown primarily for food uses can be divided into milo, kafir, hegari, feterita and hybrids (Purseglove, 1972). There are other classes of sorghums such as sorghos, grass sorghums, broom-corn sorghum and special-purpose sorghum.

The sorghum kernel varies in colour from white through shades of red and brown to pale yellow to deep purple-brown. The most common colours are white, bronze and brown. Kernels are generally spherical but vary in size and shape. The caryopsis can be rounded and bluntly pointed, 4 to 8 mm in diameter (Purseglove, 1972). The 1 000-kernel weight has a very wide range of values, from 3 to 80 g, but in the majority of varieties it is between 25 and 30 g. The grain is partially covered with glumes. Large grains with corneous endosperm are usually preferred for human consumption. Yellow endosperm with carotene and xanthophyll increases the nutritive value. Sorghum grain that has a testa contains tannin in varying proportions depending on the variety.

PEARL MILLET

Pearl millet, *Pennisetum glaucum*, is also known as spiked millet, *bajra* (in India) and bulrush millet (Purseglove, 1972). Pearl millet may be considered as a single species but it includes a number of cultivated races. It almost

certainly originated in tropical western Africa, where the greatest number of both wild and cultivated forms occurs. About 2 000 years ago the crop was carried to eastern and central Africa and to India, where because of its excellent tolerance to drought it became established in the drier environments.

The height of the pearl millet plant may range from 0.5 to 4 m and the grain can be nearly white, pale yellow, brown, grey, slate blue or purple. The ovoid grains are about 3 to 4 mm long, much larger than those of other millets, and the 1 000-seed weight ranges from 2.5 to 14 g with a mean of 8 g. The size of the pearl millet kernel is about one-third that of sorghum. The relative proportion of germ to endosperm is higher than in sorghum.

MINOR MILLETS

Minor millets (also referred to as small millets) (Seetharam, Riley and Harinarayana, 1989) have received far less attention than sorghum in terms of cultivation and utilization. They include finger millet (*Eleusine coracana*), foxtail millet (*Setaria italica*), kodo millet (*Paspalum scrobiculatum*), common or proso millet (*Panicum miliaceum*), little millet (*Panicum sumatrense*) and barnyard or sawa millet (*Echinochloa crus-galli* and *Echinochloa colona*) (Table 1). More information is available on finger millet than on any of the others. Minor millets account for less than one percent of the foodgrains produced in the world today. Thus they are not important in terms of world food production, but they are essential as food crops in their respective agro-ecosystems. They are mostly grown in marginal areas or under agricultural conditions where major cereals fail to give sustainable yields. Detailed descriptions of these millets are given by Purseglove (1972).

Finger millet

Finger millet, *Eleusine coracana* L., is also known as African millet, koracan, *ragi* (India), *wimbi* (Swahili), *bulo* (Uganda) and *telebun* (the Sudan). It is an important staple food in parts of eastern and central Africa and India. It is the principal cereal grain in northern and parts of western Uganda and northeastern Zambia. The grains are malted for making beer.

Finger millet can be stored for long periods without insect damage (Purseglove, 1972) and thus it can be important during famine. Numerous cultivars have been identified. In India and Africa, two groups are recognized: African highland types with grains enclosed within the florets; and Afro-Asiatic types with mature grains exposed outside the florets. It is believed that Uganda or a neighbouring region is the centre of origin of *E. coracana*, and it was introduced to India at a very early date, probably over 3 000 years ago. Though finger millet is reported to have reached Europe at about the commencement of the Christian era, its utilization is restricted mostly to eastern Africa and India.

The height of cultivars varies from 40 cm to 1 m and the spike length ranges from 3 to 13 cm. The colour of grains may vary from white, through orange-red, deep brown and purple, to almost black. The grains are smaller than those of pearl millet, and the mean 1 000-seed weight is about 2.6 g.

Foxtail millet

Foxtail millet, *Setaria italica* L., is also known as Italian, German, Hungarian or Siberian millet. It is generally considered to have been domesticated in eastern Asia, where it has been cultivated since ancient times. The main production area is China, but *S. italica* is the most important millet in Japan and is widely cultivated in India (Purseglove, 1972). It is believed to have been one of the five sacred plants of ancient China (from 2700 BC). Because of its short duration it is a suitable crop for growing by nomads, and it was probably brought to Europe in this way during the Stone Age, as seeds abound in the Lake Dwellings in Europe.

The height of the plants varies from 1 to 1.5 m and the colour of the grain varies from pale yellow, through orange, red and brown, to black. The 1 000-seed weight is about 2 g.

Common millet

Common millet, *Panicum miliaceum* L., is also known as proso millet, hog millet, broom-corn millet, Russian millet and brown corn. This millet is of ancient cultivation. It is the *milium* of the Romans and the true millet of history. It was cultivated by the early Lake Dwellers in Europe. It is believed

to have been domesticated in central and eastern Asia and because of its ability to mature quickly was often grown by nomads.

The shallow-rooted plant varies in height between 30 and 100 cm. The grain contains a comparatively high percentage of indigestible fibre because the seeds are enclosed in the hulls and are difficult to remove by conventional milling processes. The 1 000-seed weight is about 5 g (varying between 4.7 and 7.2 g). Common millet is particularly suited to dry continental conditions and grows in more temperate climates than other millets.

Little millet

Little millet, *Panicum sumatrense* Roth ex Roemer & Schultes, is grown throughout India to a limited extent up to altitudes of 2 100 m but is of little importance elsewhere. It has received comparatively little attention from plant breeders. The plant varies in height between 30 and 90 cm and its oblong panicle varies in length between 14 and 40 cm. The seeds of little millet are smaller than those of common millet.

Barnyard millet

Barnyard, Japanese barnyard or sawa millet [*Echinochloa crus-galli* (L.) P.B. and *Echinochloa colona* (L.) Link] is the fastest growing of all millets and produces a crop in six weeks. It is grown in India, Japan and China as a substitute for rice when the paddy fails. It is grown as a forage crop in the United States and can produce as many as eight harvests per year. The plant has attracted some attention as a fodder in the United States and Japan. The height of the plant varies between 50 and 100 cm.

Kodo millet

Kodo millet, *Paspalum scrobiculatum* L., is a minor grain crop in India but is of great importance in the Deccan Plateau. Its cultivation in India is generally confined to Gujarat, Karnataka and parts of Tamil Nadu. It is classified into the groups Haria, Choudharia, Kodra and Haria-Choudharia depending on panicle characters. Kodo is an annual tufted grass that grows to 90 cm high. Some forms have been reported to be poisonous to humans and animals, possibly because of a fungus infecting the grain. The grain is

enclosed in hard, corneous, persistent husks that are difficult to remove. The grain may vary in colour from light red to dark grey.

GRAINS AND THEIR STRUCTURE

Kernels of sorghum and millets show considerable diversity in colour, shape, size and certain anatomical components (Table 2).

The basic kernel structure is similar in sorghum and different millets. The principal anatomical components are pericarp, germ or embryo and endosperm. In finger, proso and foxtail millets the pericarp is like a sack, loosely attached to the endosperm at only one point. In these utricle-type kernels the pericarp easily breaks away, leaving the seed-coat or testa to protect the inner endosperm. The kernels of sorghum and pearl millet are of the caryopsis type, in which the pericarp is completely fused to the endosperm.

The relative distribution of the three main kernel components varies. In the sorghum kernel the distribution by weight is pericarp 6 percent, endosperm 84 percent and germ 10 percent (Hubbard, Hall and Earle, 1950). In pearl millet, it is pericarp 8.4 percent, endosperm 75 percent and germ 16.5 percent (Abdelrahman, Hoseney and Varriano-Marston, 1984). The ratio of endosperm to germ in pearl millet is 4.5:1, while in the sorghum kernel it is 8.4:1. In finger and proso millets the germ is very small and therefore the endosperm-to-germ ratio, 11:1 to 12:1, is much higher than in sorghum.

Pericarp

Pericarp is the outermost structural component of the caryopsis and is composed of three sublayers, namely epicarp, mesocarp and endocarp. The epicarp is further divided into epidermis and hypodermis. In the sorghum caryopsis, the epidermis is composed of thick, elongated, rectangular cells which have a coating of cutin on the outer surface. Often a pigment is present in the epidermis. The hypodermis is composed of slightly smaller cells than the epidermis and is one to three cell layers in thickness. The mesocarp, the middle part, is the thickest layer of the sorghum pericarp, but its thickness varies widely among genotypes. Mould resistance in sorghum is associated

TABLE 2

Structural features of kernels of sorghum and some millets

Grain	Type	Shape	Colour	1 000-kernel weight (g)
Sorghum	Caryopsis	Spherical	White, yellow, red, brown	25-30
Pearl millet	Caryopsis	Ovoid, hexagonal, globose	Grey, white, yellow, brown, purple	2.5-14
Finger millet	Utricle	Globose	Yellow, white, red, brown, violet	2.6
Proso millet	Utricle			4.7-7.2
Foxtail millet	Utricle			1.86

Grain	Seed-coat			Aleurone	
	Number of layers	Pigmented	Thickness (μm)	Number of layers	Cell size (μm)
Sorghum	1	Sometimes	0.4	1	
Pearl millet	1	Sometimes	0.4	1	16-30 x 5-15
Finger millet	5	Yes	10.8-24.2	1	18 x 7.6
Proso millet	1	No	0.2-0.4	1	12 x 6
Foxtail millet	1			1	

Grain	Starch granules					Protein bodies	
	Diameter (μm)	Peripheral zone (μm)	Corneous zone (μm)	Floury zone (μm)	Type	Size (μm)	Location
Sorghum	20-30				Simple	0.3-3	All areas
Pearl millet	10-12	6.4	6.4	7.6	Simple	0.6-0.7	All areas
Finger millet	3-21	8-16.5	3-19	11-21	Simple/compound	2.0	Peripheral/corneous
Proso millet	2-10	3.9	4.1	4.1	Simple	0.5-1.7	Peripheral
Foxtail millet	10						

TABLE 2 (*continued*)

Grain	Germ	
	Size (μm)	Endosperm:germ ratio
Sorghum		8.4:1
Pearl millet	1 420 x 620	4.5:1
Finger millet	980 x 270	11:1
Proso millet	1 100 x 310	12:1
Foxtail millet		12:1

with thin mesocarp. Grains with thick mesocarp on a hard endosperm are preferred for dehulling by hand-pounding. The endocarp, the innermost sublayer of the pericarp, consists of cross cells and a layer of tube cells which transport moisture into the kernel. During dry milling of sorghum, the breakage occurs at the cross and tube cell layers.

The pericarp of the pearl millet caryopsis consists of an epicarp with one or two cell layers, a mesocarp that varies in thickness because of genetic factors and an endocarp made up of cross and tube cells. The mesocarp layer of pearl millet does not contain starch granules; these are found only in sorghum mesocarp. During decortication or milling, the pericarp of pearl millet breaks at the cross and tube cell layers and fragments of endocarp may remain with the endosperm.

Seed-coat or testa

Just underneath the endocarp is the testa layer or seed-coat. In some sorghum genotypes the testa is highly pigmented. The presence of pigment and the colour are a genetic character. The thickness of the testa layer is not uniform. It is thick near the crown area of the kernel and thin near the embryo portion. In some genotypes there is a partial testa, while in others it is not apparent or is absent. In pearl millet the testa layer is thin and sometimes pigmented. In other millets the testa is always pigmented and is only a single layer thick. In finger millet the testa is very thick, with five cell layers, and is also pigmented.

Endosperm

The largest component of the cereal kernel is the endosperm, which is a major storage tissue. It is composed of an aleurone layer and peripheral corneous and floury zones. In all the millets and sorghum, the aleurone layer is a single layer of cells which lies just below the seed-coat or testa. The aleurone cells are rich in minerals, B-complex vitamins and oil and contain some hydrolysing enzymes.

The peripheral endosperm is distinguished by long rectangular cells which are densely packed and contain starch granules and protein bodies enmeshed in the protein matrix. The starch in these cells is therefore not easily available for enzyme digestion, unless the protein associated with it is also reduced (Chandrashekhar and Kirleis, 1988). The matrix protein in general is alkali-soluble glutelin and the protein bodies are alcohol-soluble prolamins which account for the largest proportion of total protein in the kernel.

The protein bodies in the endosperm of sorghum and millets are spherical and differ in size among species and also within the endosperm of a single kernel. In sorghum the number of protein bodies decreases as the starch content increases from the peripheral zone to the central core where the floury endosperm is located. In pearl millet the protein bodies are more numerous in the floury than in the corneous zone. Adams, Novellie and Liebenberg (1976) have reported the presence of several enzymes, e.g. protease, 3-glucosidases, 3-galactosidase and phosphatases, in the protein bodies of sorghum. The protein bodies of sorghum, pearl millet and finger millet also contain phosphorus, calcium, potassium and magnesium.

The starch granules of corneous endosperm are polyhedral and differ in size in different millet species. In floury endosperm the starch granules are spherical and bigger than the starch granules of the corneous zone. The starch in the floury zone is more amenable to enzyme digestion. In pearl and finger millets, the starch granules of the floury endosperm are spherical and big. The starch in pearl millet is hydrolysed more slowly than that of sorghum by hog pancreatic amylase (Sullins and Rooney, 1977).

The proportions of corneous and floury endosperm determine the texture of the millet kernel. In soft-textured kernels there is more floury than

corneous endosperm. In hard-textured kernels, on the other hand, there is more densely packed corneous endosperm than floury endosperm. Foxtail millet contains very little floury endosperm and is of a hard, corneous texture. Finger and proso millet kernels, with the endosperm evenly divided between the corneous and floury zones, are of intermediate texture. In pearl millet and sorghum the kernel texture varies widely, from all floury, very soft endosperm to all corneous, very hard or vitreous endosperm.

Grain texture is one of the most important determinants of the processing and food quality of sorghum and millets (Rooney, Kirleis and Murty, 1986). Hard-endosperm sorghum when decorticated gives fewer breakens and more full grains than softer-endosperm sorghum (Desikachar, 1982). In dry milling, the flour yield is higher in corneous than in soft floury types. On the other hand, in wet milling the starch yield is higher in soft-endosperm genotypes. In the preparation of thick porridge, varieties with a higher proportion of vitreous endosperm are preferred. Such varieties are also suitable for popping (Chandrashekhar and Desikachar, 1986; Murty, Patil and House, 1982). For preparation of bread, fermented or unfermented, the flour of soft-endosperm sorghum is highly preferred (Rooney, Kirleis and Murty, 1986).

Germ

The embryonic axis and the scutellum are the two major parts of the germ. The scutellum is a storage tissue rich in lipids, protein, enzymes and minerals. In pearl millet the ratio of germ to endosperm is larger than in sorghum and other millet kernels. The oil in the sorghum germ is rich in polyunsaturated fatty acids and is similar to corn oil (Rooney, 1978).

Chapter 2

Production and utilization

The production and consumption data on sorghum and millets can be considered as only the best estimates that are available, as production data from small subsistence farms are difficult to obtain in any country. It is also likely that grain distribution and consumption throughout the semi-arid tropical regions vary widely among seasons, communities and families. Detailed and reliable data on the variety of products made from sorghum and millets and the prevalence of their use are either scanty or currently unavailable. One reason for the lack of information is the fact that to collect this information extensive surveys are needed. Several factors such as cost, time, labour, transportation and accessibility of villages in rural areas have to be considered before a survey is carried out. In several developing countries, inadequate infrastructure and other constraints have contributed to the lack of information on consumption of sorghum and millets.

SORGHUM PRODUCTION

The total production of sorghum in the world in 1990 was 58 million tonnes, a decrease from 60 million tonnes in the year 1989 and 62 million tonnes in 1988 (FAO, 1991). A decrease in yield from 1 340 kg/ha in 1989 to 1 312 kg/ha in 1990 was reported, while the area remained around 44 million hectares in both years. Table 3 provides data on area, yield and production of sorghum in various regions of the world.

The five largest producers of sorghum in the world (Table 4) are the United States (25 percent), India (21.5 percent), Mexico (almost 11 percent), China (9 percent) and Nigeria (almost 7 percent). Together these five countries account for 73 percent of total world production.

Of the total world area devoted to sorghum, over 80 percent is in developing countries. In Africa, sorghum is grown in a large belt that spreads

TABLE 3

Area, yield and production of sorghum by region, 1990

Region	Area		Yield (kg/ha)	Production	
	(10 ³ ha)	(% of total)		(10 ³ t)	(% of total)
North and Central America	5 970	13.5	3 572	21 325	36.7
Asia	18 451	41.6	1 023	18 867	32.4
Africa	17 799	40.1	718	12 784	22.0
South America	1 353	3.1	2 614	3 537	6.1
Oceania	407	0.9	2 298	934	1.6
World (1990)	44 352		1 312	58 190	
World (1989)	44 695		1 340	59 991	

Source: FAO, 1991.

TABLE 4

Leading sorghum producers, 1990

Country	Area		Production	
	(10 ³ ha)	(% of total)	(10 ³ t)	(% of total)
United States	3 674	8.3	14 516	25.0
India	15 300	34.5	12 500	21.5
Mexico	1 830	4.1	6 230	10.7
China	1 900	4.3	5 310	9.1
Nigeria	6 000	13.5	4 000	6.9
Argentina	688	1.6	2 016	3.5
Sudan	2 925	6.6	1 502	2.6
Ethiopia	870	2.0	1 000	1.7
Australia	406	0.9	933	1.6
Burkina Faso	1 250	2.8	917	1.6
Total	34 843	78.6	48 924	84.1
World	44 352	100	58 190	100

Source: FAO, 1991.

from the Atlantic coast to Ethiopia and Somalia, bordering the Sahara in the north and the equatorial forest in the south. This area extends through the drier parts of eastern and southern Africa, where rainfall is too low for the successful cultivation of maize. Sorghum is the second most important cereal (after maize) in sub-Saharan Africa.

Because of higher yield per unit area, North and Central America produce the highest quantity of sorghum (37 percent of total production). In Central and South America sorghum is grown in the drier parts of Mexico, El Salvador, Guatemala, Nicaragua, dry lowland interior areas of Argentina, dry areas of northern Colombia, Venezuela, Brazil and Uruguay. In North America, sorghum is cultivated in parts of the central and southern plains of the United States where rainfall is low and variable. Kansas, Texas, Nebraska and Arkansas are the major producing states, accounting for about 80 percent of total production in the United States.

In Asia, sorghum is extensively cultivated in India, China, Yemen, Pakistan and Thailand. Production in Europe is limited to a few areas in France, Italy, Spain and the southeastern countries. In Oceania, Australia is the only producer of significance; the production is concentrated in Queensland and northern New South Wales, where about 95 percent of the total crop is produced.

World sorghum production expanded from 40 million tonnes at the beginning of the 1960s to 66 million tonnes in 1979-81. However, by 1990 it had fallen to 58 million tonnes, though the area under sorghum declined only slightly, from 45.6 million to 44.4 million hectares, during the same period. The reduction in production from 1979-81 to 1990 was largely due to a decline in two major sorghum-producing countries, the United States and China. These two countries accounted for 6.2 million tonnes or 85 percent of the reduction in the global production figures. There are several reasons for the declining trend in the production of sorghum, including unpredictable and erratic distribution of rainfall (most of the sorghum grown is rain-fed), declining soil fertility, the inefficient production systems employed in individual countries, biotic and abiotic stresses and declining demand for sorghum. The growth in food demand (2.9 percent) for the period 1980 to 2000 in 90 developing countries will marginally exceed

TABLE 5

Sources of energy and protein in the food supply of the world's ten leading sorghum producers, 1987-89

Country	Energy per caput per day (kcal)				Protein per caput per day (g)			
	Total	From vegetable products	Percentage of total	From animal products	Total	From vegetable products	Percentage of total	From animal products
United States	3 676	2 430	66.1	1 246	109.6	36.4	33.2	73.2
India	2 196	2 048	93.3	2 048	53.2	45.6	85.7	7.6
Mexico	3 048	2 497	81.9	551	77.9	46.9	60.2	31.0
China	2 634	2 365	89.8	269	62.8	50.7	80.7	12.1
Nigeria	2 306	2 248	97.5	58	49.5	43.6	88.1	5.9
Argentina	3 110	2 145	69.0	965	100.3	36.5	36.4	63.8
Sudan	2 028	1 677	82.7	351	57.8	37.6	65.1	20.2
Australia	3 186	2 036	63.9	1 150	97.4	31.7	32.5	65.7
Burkina Faso	2 286	2 186	95.6	100	69.8	62.6	89.7	7.2

Source: FAO, 1991.

projected agricultural production growth (2.8 percent) (FAO, 1981). However, the imbalance will be more pronounced in Africa (demand 3.4 percent, production growth 2.6 percent). In the least-developed countries, production growth is predicted to lag 25 percent below the growth of demand.

In 1987-89, vegetable products supplied the bulk of dietary energy (90 percent or more) and more than 80 percent of total daily protein in four of the ten major producers of sorghum in the world, namely, India, China, Nigeria and Burkina Faso (Table 5). In Mexico and the Sudan, vegetable products supplied more than 80 percent of dietary energy.

SORGHUM UTILIZATION

Total consumption of sorghum closely follows the global pattern of output, since most of it is consumed in the countries where it is grown. Sorghum is used for two distinct purposes: human food and animal feed. Although in the early 1960s a very large part of the sorghum output was used directly as

TABLE 6

Sorghum utilization, 1981-85 average and growth from 1961-65 to 1981-85

Region	1981-85 average (million tonnes)				Annual growth from 1961-65 to 1981-85 (%)			
	Food	Feed	Other uses	Total	Food	Feed	Other uses	Total
Africa	8.0	0.4	2.3	10.7	1.5	3.5	-0.6	1.0
Asia	15.1	6.3	2.1	23.5	-	7.8	0.2	1.2
Central America	0.3	8.4	0.2	8.9	2.0	13.2	-	12.1
South America	-	4.6	0.3	4.9	-	8.5	5.7	8.3
North America	-	12.6	0.1	12.7	-	0.5	-	0.5
Europe	-	1.4	-	1.4	-	-2.5	-	-2.5
USSR	-	2.3	0.3	2.6	-	17.0	-	17.0
Oceania	-	0.4	-	0.4	-	3.5	-	3.5
World	23.4	36.4	5.3	65.1	0.5	3.8	0.4	2.1
Developing countries	23.2	15.6	4.8	43.6	0.5	10.3	0.1	1.7
Developed countries	0.2	20.8	0.5	21.5	3.5	1.7	4.7	2.2

Source: FAO, 1988.

human food, its share has continuously declined since then. In fact, consumption of sorghum as animal feed has more than doubled, from 30 to 60 percent, since the early 1960s, while the volume of total food use has remained unchanged or has slightly declined (Table 6). In North and Central America, South America and Oceania most of the sorghum produced is used for animal feed.

Human food

While total food consumption of all cereals has risen considerably during the past 35 years, world food consumption of sorghum has remained stagnant, mainly because, although nutritionally sorghum compares well with other grains, it is regarded in many countries as an inferior grain. Per caput consumption of sorghum is high in countries or areas where climate does not allow the economic production of other cereals and where per caput

incomes are relatively low. These include especially the countries bordering the southern fringes of the Sahara, including Ethiopia and Somalia, where the national average per caput consumption of sorghum can reach up to 100 kg per year. Other countries with significant per caput consumption include Botswana, Lesotho, Yemen and certain provinces in China and states in India. In most other countries food consumption of sorghum is relatively small or negligible compared to that of other cereals.

More than 95 percent of total food use of sorghum occurs in countries of Africa and Asia (Table 6). In Africa, human consumption accounts for almost three-quarters of total utilization and sorghum represents a large portion of the total calorie intake in many countries. For example, in Burkina Faso about 45 percent of the total annual calorie intake from cereals comes from sorghum, although its share has declined from 55 percent in the early 1960s. China and India account for about 90 percent of total food use in Asia.

Available data from Africa indicate that despite an increase in total food use between the early 1960s and the mid-1980s, the average per caput consumption declined from 20 to 15 kg per year (FAO, 1988). Decreases were concentrated in Kenya, Mozambique, Nigeria and Somalia but occurred also in Botswana, Ethiopia, Lesotho and Zimbabwe. In Asia, both total and per caput food use of sorghum declined.

This decline in per caput consumption in many countries was due in part to shifts in consumer habits brought about by a number of factors: the rapid rate of urbanization, the time and energy required to prepare food based on sorghum, inadequate domestic structure, poor marketing facilities and processing techniques, unstable supplies and relative unavailability of sorghum products, including flour, compared with other foodstuffs. Changes in consumption habits were concentrated in urban areas. Per caput food consumption of sorghum in rural producing areas remained considerably higher than in the towns. In addition, national policies in a number of countries had a negative influence on sorghum utilization as food. For instance, large imports of cheap wheat and rice and policies to subsidize production of those crops in some countries had considerable negative impact on the production of sorghum.

Animal feed

Grain use for animal feed has been a dynamic element in the stimulation of global sorghum consumption. The demand for sorghum for feed purposes has been the main driving force in raising global production and international trade since the early 1960s. The demand is heavily concentrated in the developed countries, where animal feed accounts for about 97 percent of total use, and in some higher-income developing countries, especially in Latin America where 80 percent of all sorghum is utilized as animal feed. The United States, Mexico and Japan are the main consuming countries, followed by Argentina, the former Soviet Union and Venezuela. These countries together account for over 80 percent of world use of sorghum as animal feed.

MILLET PRODUCTION

Several kinds of millets are grown in the world, but FAO data on area, yield and production of all millets are given together under the general heading of millet. Pearl millet, finger millet and proso millet account for a large proportion of the world production. Millet production increased from 26 million tonnes in 1979-81 to 31 million tonnes in 1988 and was similar in 1989 and 1990. Asia, Africa and the former Soviet Union produce almost all the world's millets, as shown in Table 7. The major producers of millets in 1990 were India (39 percent), China (15 percent), Nigeria (13 percent) and the Soviet Union (12 percent) (Table 8).

The area under millet production decreased marginally from 38.1 million hectares in 1979-81 to 37.6 million hectares in 1990. However, production increased by 17 percent, from 25.6 million tonnes in 1979-89 to 29.8 million tonnes in 1990, largely because of production increases in Nigeria (65 percent), India (25 percent) and the Soviet Union (207 percent). However, there was a 24 percent decrease in production in China during the same period.

In all of the ten leading millet-producing countries except the Soviet Union, vegetable products supplied 90 percent or more of total dietary energy in 1987-89 (Table 9). In India, China, Nigeria, the Niger, Mali, Uganda, Burkina Faso and Nepal, vegetable products supplied more than 80

TABLE 7

Area, yield and production of millet, by region, 1990

Region	Area		Yield (kg/ha)	Production	
	(10 ³ ha)	(% of total)		(10 ³ t)	(% of total)
Asia	20 853	55.5	804	16 767	56.2
Africa	13 548	36.1	669	9 066	30.4
USSR	2 903	7.7	1 256	3 647	12.2
North and Central America	150	0.4	1 200	180	0.6
South America	55	0.2	1 655	91	0.3
Oceania	34	0.1	882	30	0.1
World	37 565	100	794	29 817	100

Source: FAO, 1991.

TABLE 8

Leading millet producers, 1990

Country	Area		Production	
	(10 ³ ha)	(% of total)	(10 ³ t)	(% of total)
India	17 000	45.3	11 500	38.6
China	2 601	6.9	4 401	14.8
Nigeria	4 000	10.7	4 000	13.4
USSR	2 903	7.7	3 647	12.2
Niger	3 100	8.3	1 133	3.8
Mali	900	2.4	695	2.3
Uganda	400	1.1	620	2.1
Burkina Faso	1 150	3.1	597	2.0
Senegal	865	2.3	514	1.7
Nepal	200	0.5	240	0.8
Total	33 119	88.2	27 347	91.7
World (1990)	37 565		29 817	
World (1989)	37 409		29 962	

Source: FAO, 1991.

TABLE 9

Sources of energy and protein in the food supply of the world's ten leading millet producers, 1987-89

Country	Energy per caput per day (kcal)				Protein per caput per day (g)			
	Total	Vegetable products	Percentage of total	Animal products	Total	Vegetable products	Percentage of total	Animal products
India	2 196	2 048	93.3	148	53.2	45.6	85.7	7.6
China	2 634	2 365	89.8	269	62.8	50.7	80.7	12.1
Nigeria	2 306	2 248	97.5	58	49.5	43.6	88.1	5.9
USSR	3 380	2 444	72.3	936	106.2	50.1	47.2	56.1
Niger	2 297	2 152	93.7	145	64.0	53.2	83.1	10.8
Mali	2 234	2 090	93.6	144	62.5	50.1	80.2	12.4
Uganda	2 136	2 010	94.1	126	48.1	38.7	80.5	9.4
Burkina Faso	2 286	2 186	95.6	100	69.8	62.6	89.7	7.2
Senegal	2 374	2 160	91.0	214	68.2	49.9	73.0	18.3
Nepal	2 074	1 937	93.4	137	52.5	44.8	85.3	7.7

Source: FAO, 1991.

percent of protein. Thus in many sorghum- and millet-producing countries, vegetable products, especially cereals, provide the bulk of energy and protein.

MILLET UTILIZATION

Of the 30 million tonnes of millet produced in the world about 90 percent is utilized in developing countries and only a tiny volume is used in the developed countries outside the former Soviet Union. Exact statistical data are unavailable for most countries, but it is estimated that a total of 20 million tonnes are consumed as food, the rest being equally divided between feed and other uses such as seed, the preparation of alcoholic beverages and waste. Six countries (China, Ethiopia, India, the Niger, Nigeria and the former Soviet Union) are estimated to account for about 80 percent of global millet utilization (Table 10).

TABLE 10

Estimated millet utilization, 1981/82 to 1985/86 average

Region or country	Food (10 ³ t)	Feed (10 ³ t)	Other uses ^a (10 ³ t)	Total (10 ³ t)	Per caput food use (kg/yr)
Africa ^b	7 094	122	1 921	9 137	13.5
Burkina Faso	381	—	60	441	50.8
Ethiopia	1 020	—	196	1 216	24.9
Mali	516	1	88	605	67.7
Niger	977	21	215	1 213	168.9
Nigeria	2 365	86	700	3 151	26.5
Senegal	397	2	80	479	64.4
Uganda	259	47	150	456	17.8
Asia	14 441	1 665	1 305	17 411	5.3
China	4 857	1 120	480	6 457	4.7
India	8 794	150	710	9 664	11.9
Central America	—	—	—	—	—
South America	—	91	5	96	—
North America	—	104	6	110	—
Europe	—	104	6	110	—
USSR	800	1 107	400	2 307	2.9
Oceania	—	13	2	15	—
World	22 335	3 144	3 642	29 121	4.8
Developing countries	21 535	1 878	3 231	26 644	6.1
Developed countries	800	1 266	411	2 477	0.7

^a Food seed, manufacturing purposes and waste.^b Including fonio and teff.

Source: FAO, 1990b.

Human food

Per caput food consumption of millet varies greatly among countries, though it is highest in Africa. In the Sahel, millet is estimated to account for about one-third of total cereal food consumption in Burkina Faso, Chad and the Gambia, roughly 40 percent in Mali and Senegal and over two-thirds in

the Niger. Other countries in Africa where millet is a significant food item include Ethiopia, Nigeria and Uganda. Millet is also an important food item for the population living in the drier parts of many other countries, especially in eastern and central Africa but also in the northern coastal countries of western Africa. In developing countries outside Africa, millet has local significance as a food in parts of some countries such as China, India, Myanmar and the Democratic People's Republic of Korea. Although national per caput levels are rather low in the countries that consume the most millet, i.e. China and India, food use of millet is important in certain areas of these countries.

World consumption of millet as food has only grown marginally during the recent past in contrast to the significant increase in consumption of other cereals. There has been a tendency in all countries for the per caput consumption of millet to decline when per caput income exceeds certain levels because of the lower prestige associated with its consumption. The other reasons for stagnating consumption are the same as those discussed above for sorghum.

Animal feed

Utilization of millet as animal feed is negligible in absolute terms and compared with other uses and other cereals. It has been estimated that only about 10 percent of the millet used globally is fed to animals.

REGIONAL TRENDS IN PRODUCTION AND UTILIZATION OF SORGHUM AND MILLETS

West Africa

The West African semi-arid tropics are defined as those areas where rainfall exceeds potential evapotranspiration for two to seven months annually. This area encompasses all of Senegal, the Gambia, Burkina Faso and Cape Verde, major southern portions of Mauritania, Mali and the Niger and the northern portions of Côte d'Ivoire, Ghana, Togo, Benin and Nigeria. Cereals occupy nearly 70 percent of total cultivated area in this region and engage 50 to 80 percent of total farm-level resources (Matlon, 1990). Millets and sorghum account for 80 percent of cereal production. During the last 25 years growth

in millet and sorghum production has been slow and the total output has been about 1 percent lower than the population growth per year. Average yield per unit area of millet and sorghum has declined during this period, and the small production increases have primarily resulted from expansion of cropped area. Many factors have contributed to the decreased productivity, including demographic pressure and ecological degradation.

The West African semi-arid tropics can be classified into four agroclimatic zones: Sahelian (annual rainfall <350 mm), Sudano-Sahelian (350 to 600 mm), Sudanian (600 to 800 mm) and Sudano-Guinean (800 to 1 100 mm). According to Matlon (1990), the potential for major increases in sorghum and millet supply exist only in the Sudano-Guinean zone and to a lesser extent in the Sudanian zone. Yield stabilization and land conservation technologies should be given highest priority in these two zones.

Reardon and Matlon (1989) reported the food consumption patterns of the population of two villages, one representing Sahelian savannah and the other the Sudano-Sahelian zone. Market dependence was considerably lower among households in the Sudano-Sahelian village and was more equally distributed across income strata than in the Sahelian village. The poor were especially vulnerable in the rainy season when they were more dependent on the market. In fact, purchased food products contributed 60 to 70 percent of all calories consumed by poor and middle-income households during the rainy season. In the Sahelian village white sorghum accounted for only 4 percent of the cropping area but provided nearly 25 percent of the calories consumed outside the harvest season by poor households. Red sorghum and maize accounted for only 10 percent of the cultivated area but provided up to 60 percent of the calories consumed by the poor during non-harvest seasons.

Table 11 shows household expenditures on various cereals (represented by shares of total expenditure) in Burkina Faso, the Gambia, Mali, the Niger and Senegal (Reardon, 1993). These data were obtained from surveys done in good and poor harvest years. They show that rice is an important item in the urban diets of the Sahel, perhaps because of the relatively low cost of imported rice as a result of the decline in coarse-grain production, the perceived desire of consumers to emulate the dietary habits of high-income

TABLE 11
Cereal consumption in the Sahel: survey results^a

Population sample	Rice	Millet	Sorghum	Maize	Wheat	Other	Total
BURKINA FASO							
Ouagadougou (1984/85)							
Overall	41	16	12	15	17	— ^b	100
Poorest tercile	45	17	15	15	9	—	100
Richest tercile	35	13	8	12	32	—	100
Ouagadougou (1982/83)							
Overall	52	6	31	4	7	—	100
Poorest tercile	55	8	33	1	3	—	100
Richest tercile	52	3	20	5	20	—	100
Rural (1984/85)							
Sahelian zone	1	47	29	21	1	—	100
Sudanian zone	0	11	72	16	1	—	100
Guinean zone	6	22	57	14	1	—	100
GAMBIA							
Rural (1985/86)							
Overall	75	23 ^c		3	—	—	100
MALI							
Bamako (1985/86)							
Overall	57	19	<0.5	1	17	6	100
Poorest quarter	55	20	1	<0.5	16	8	100
Richest quarter	54	21	1	0	19	5	100
Other cities (1985/86)							
Overall	54	21	1	0	19	5	100
Rural							
Bougouni	8	83 ^c		6	—	3	100
Kayes	4	21 ^c		74	—	1	100

TABLE 11 (*continued*)

Population sample	Rice	Millet	Sorghum	Maize	Wheat	Other	Total
NIGER							
Niamey (1988/89)^d							
Overall	55	36	2	16	<0.5	—	100
Rural (1988/89)							
Tillabery	17	70	15	<0.5	<0.5	—	100
Diffa	1	53	16	24	5	—	100
SENEGAL							
Dakar (1983)							
Overall	66	31	—	3	—	—	100
Other urban							
Dioubel	37	48 ^c	—	<0.5	13	—	100
Rural							
Mid-Casamance	87	8 ^c	—	5	<0.5	—	100
Rural Kaolack	11	78 ^c	—	8	3	—	100
Sahelian zone	48	26	0	4	<0.5	—	100
Sudanian zone	15	74	<0.5	<0.5	<0.5	—	100

^aThis table presents expenditure or budget shares which are product shares of total expenditure in cash terms (the sum of the imputed value of own consumption plus transfers plus purchases).

^b—; Not reported.

^cMillet and sorghum reported together.

^dFigures only given in shares of cereal budget in physical terms.

Source: Reardon, 1993.

groups or the West, the relatively easy processing and fast cooking time for rice and the availability of fast foods made with rice from street vendors. Generally the combined share of millets and sorghum exceeds that of maize in the urban diets of the Sahel. In rural diets, however, coarse grains dominate except in a few isolated cases. However, purchased food forms a substantial share of rural diets.

There is an urgent need to develop suitable processing and milling methods for sorghum and millets. Development of innovative ready-to-eat

products from these grains that could be sold by street vendors and markets would open up new avenues of utilization and could reduce the dependence on imported rice.

Eastern and southern Africa

Sorghum and millets account for 23 percent of the cereal production of the South African Development Community (SADC) countries, which include Angola, Botswana, Lesotho, Malawi, Mozambique, Namibia, Swaziland, the United Republic of Tanzania, Zambia and Zimbabwe. However, they are dominant grain crops only in Botswana and Namibia, where they account for 86 and 50 percent of total cereal production, respectively. Sorghum and millets are important in those areas that receive less than 650 mm of annual rainfall. The productivity of these crops is low, and in most SADC countries there is no strategy for the development of sorghum and millet subsectors.

In most SADC countries formal-sector (government-regulated) markets handle only a very small proportion of total sorghum and millet production (Table 12). They handle less than 10 percent of total production in Lesotho, Swaziland, the United Republic of Tanzania, Zambia and Zimbabwe. Most of the sorghum and millets produced in the SADC region is consumed by producing households or sold in informal markets, primarily for traditional beer production. Maize is cheaper than sorghum in many informal markets across the SADC region, and there may be good potential for expanding the production of sorghum and millets in view of the price differences.

One of the reasons that have been suggested for not increasing the production of sorghum and millets is that the productivity of these crops is low. Their average yields are lower than those of maize even in the semi-arid areas of the SADC. Although the total production costs are often lower than those for maize, the productivity of small grains measured in terms of returns of labour tends to be low. Under certain conditions, finger millet has been reported to offer higher economic returns than maize (Table 13). However, it requires more labour input than maize, which limits its production (Rohrbach, 1991).

To make sorghum and millets competitive it is necessary to improve their productivity with an assured quality of the grain. The area under sorghum

TABLE 12

Coarse grain production sold through formal market channels in SADC countries (%)

Country	Sorghum	Pearl millet	Finger millet	Maize
Zimbabwe (1989/90)	8	9	3	62
Tanzania (1986/87)	1 ^a	—	—	7
Zambia (1987/88)	1	1	1	69
Botswana (1985)	25	—	—	62
Lesotho (1989)	1	—	—	—
Swaziland (1990)	1	—	—	—

^a Sorghum and millets combined.

Source: Rohrbach, 1991.

TABLE 13

Returns per labour hour in Zimbabwe during the 1988/89 cropping season^a

Sector/crop	Total labour (hr)	Average yield (t/ha)	Average price (Z\$/kg)	Gross margin (Z\$/ha)	Returns per labour hour (Z\$/ha)
Smallholder sector					
Maize	411	1.76	0.23	233.36	0.59
Pearl millet	521	0.38	0.34	30.95	0.06
Finger millet	545	0.45	0.61	173.81	0.38
Sorghum	308	0.32	0.42	54.43	0.16
Nyajena					
Maize	360	0.44	0.30	46.71	0.13
Pearl millet	551	0.27	0.45	35.31	0.07
Finger millet	567	0.38	0.68	175.37	0.40
Sorghum	398	0.24	0.36	32.44	0.08

^a Favourable rainfall in higher average-rainfall zones; poor rainfall in Nyajena.
Source: Rohrbach, 1991.

and millets will not increase significantly unless the productivity of these grains is improved substantially. Therefore there is an urgent need to improve the production technologies for these grains and to disseminate this knowledge to the farmers' fields. Only in this way can these cereals compete locally with maize. Identifying a few well-researched alternative uses for sorghum would yield new avenues for increased utilization and thus act as a catalyst to improve production and productivity.

India

India is the world's second largest producer of sorghum. At present most of the sorghum produced in India is consumed as a human food in the form of *roti* or *chapatti* (unleavened flat bread). Walker (1990) analysed the supply and demand prospects for sorghum in India. He found that in the past three decades the average per caput sorghum consumption declined markedly in both rural and urban households. Average rural consumption fell from 1.74 to 1 kg per caput per month. Urban consumption dropped from 0.74 to 0.46 kg per caput per month. It was projected that sorghum consumption would continue to fall at about 0.5 percent per annum. The declining trend in sorghum consumption is partly due to the decline in per caput consumption of total cereals.

Decreases in consumption of sorghum were found to be proportional to increases in expenditure. Increased income is accompanied by increased consumption of wheat and rice, as products made from these cereals are easy to prepare and have better keeping quality. There is also a tendency to eat a greater variety of foods as income and urbanization increase. The price of sorghum relative to those of wheat and rice has not increased in the major sorghum-consuming regions. Therefore other factors are probably more influential than direct price considerations in explaining the fall in per caput sorghum consumption. Prospects of technological change could perhaps change the scenario for improved production and utilization of sorghum.

China

China is the fourth largest producer of sorghum in the world and in Asia it is second only to India in area and production of sorghum. About 30 percent

of the sorghum produced is used for human consumption and 60 percent for animal feed and the manufacture of alcoholic beverages (Kelley, Parthasarathy Rao and Singh, 1992). However, the importance of sorghum as a human food has declined over time. The area under sorghum has also declined, from about 2.8 million hectares in 1979-81 to 1.9 million hectares in 1990. Production has decreased correspondingly, from 7 million tonnes in 1979-81 to 5.3 million tonnes in 1990. In recent years more attention has been given to sorghum fodder and to developing suitable cultivars for this purpose.

Chapter 3

Storage and processing

When sorghum or millet is stored in developing countries, it is usually stored in small quantities in traditional containers, often on the farm. Large quantities are seldom accumulated and bulk storage is uncommon.

Processing involves the partial separation and/or modification of the three major constituents of the cereal grain – the germ, the starch-containing endosperm and the protective pericarp. Various traditional methods of processing are still widely used, particularly in those parts of the semi-arid tropics where sorghum and millets are grown primarily for human consumption. Most traditional processing techniques are laborious, monotonous and carried out by hand. They are almost entirely left for women to do. To some extent, the methods that are used have been developed to make traditional foods to suit local tastes and are appropriate for these purposes. Traditional techniques that are commonly used include decorticating (usually by pounding followed by winnowing or sometimes sifting), malting, fermentation, roasting, flaking and grinding. These methods are mostly labour intensive and give a poor-quality product. Sorghum and millets would probably be more widely used if processing were improved and if sufficient good-quality flour were made available to meet the demand (Eastman, 1980).

In general, industrial methods of processing sorghum and millets are not as well developed as the methods used for processing wheat and rice, which in most places are held in much higher regard than sorghum and millets. The potential for industrial processing of sorghum and millets is good, and attempts to develop improved industrial techniques have been made in several countries. Custom milling has had a significant impact in several African countries where it has recently been introduced. In Nigeria alone, where about 80 percent of sorghum and millets is now custom milled into

whole flour, over 2.5 million tonnes of sorghum have been processed in this way (Ngoddy, 1989).

To some extent for storage, but particularly for processing, the type of sorghum – brown, white or yellow – is important. The outward appearance is no indication of the variety's type; all three types can appear white, yellow, brown, red or purple, although brown sorghums generally have darker seed-coats than yellow and white sorghums. (Subsequently in this chapter the more widely recognized term "white" is used for both white and yellow types.) The important difference is whether there is a testa. The testa is usually brick red, and even a small amount of red testa left in the flour will give it a pronounced pinkness, which many people find objectionable. If the variety contains tannin, most of it will be found in the testa. Tannin is objectionable for two reasons: it competes for available protein and it has a bitter taste. However, this bitter taste is also a major advantage, because it makes granivorous birds dislike high-tannin sorghums. For this reason these varieties are widely grown in places where bird damage to white sorghum is severe.

The presence of a testa is controlled by two dominant genes, B_1 and B_2 (Hulse, Laing and Pearson, 1980). Wild sorghum will usually contain some of these dominant genes, so open pollination of white hybrids will tend to degenerate them to brown varieties. Repeated replanting of harvested seeds is often accompanied by increasing occurrence of seeds with a testa. Seeds with a testa are much harder to mill than seeds without a testa.

Brown sorghums tend to be softer than white sorghums and are more susceptible to insect damage under storage than white sorghums. However, they are markedly less susceptible to fungal damage in the field and in storage.

It is in processing that brown sorghums present the most difficulty, for the following reasons.

- When the pericarp is progressively removed from the outside, the testa is almost the last layer to be removed.
- When a brown sorghum has recently been wetted, the pericarp tends to separate just above the testa. If the pericarp is then rubbed off, the damp testa is still firmly attached to the endosperm.

- Brown sorghums are often quite soft and the endosperm tends to break apart if the seed is subjected to mechanical impact.

The best way of separating the testa of a brown sorghum from the endosperm is to cut the endosperm from the inside of the pericarp, as happens in roller milling. However, this is not possible using traditional methods. It is for these reasons that brown sorghums are usually only used in the production of beer, where some bitterness and some colour are not only acceptable but often preferred.

STORAGE

The objective of storage is to preserve as much as possible of the value of the grain for its intended future use. This means either retaining as high a proportion of viable seeds as possible for planting at the next harvest or preserving as much as possible of the food value of the grain for as long as possible. Several factors lead to the loss of both viability and nutrients, but globally the main causes of loss are the depredations of pests (insects, birds and rodents) and mould damage. Germination of the grain (sprouting) also results in losses, but on a smaller scale. Grain is stored by consumers and by processors for future consumption. It is also stored by commercial traders for resale, usually on the home market but occasionally for export.

Moisture in the grain and the temperature of storage are the most important physical factors that contribute to losses (FAO, 1970b). Most activity that causes losses occurs more rapidly as the temperature increases. With even minor changes in temperature, moisture will migrate and accumulate in certain areas, either near the top of the container or in places that are cooler than the rest. This often allows microbiological activity to occur in comparatively dry grain. Microbiological activity usually produces heat, and in unventilated stores, moist areas can get so hot that charring can occur. At this stage the grain is ruined. It may even burst into flames when it is exposed to air.

Storage bins are best filled early in the day when the air is cool and the humidity is often at its lowest. The grain should be packed as tightly as possible to allow insects the minimum space to move around and to breed. Sand is sometimes mixed with the grain to reduce the free space further.

TABLE 14

Damage and weight loss of sorghum and millets under home storage, India

Storage period	Percent damage		Percent weight loss	Increase in uric acid (mg/100 g)
	By weight	By number		
Sorghum				
1 month	3	3	0.2	0.0
5 months	5	6	1.5	4.3
9 months	9	11	2.4	5.4
Pearl millet				
1 month	0	0	0.1	0.0
5 months	2	2	0.2	3.3
9 months	2	4	1.0	3.6
Finger millet				
1 month	0	1	0.0	0.0
5 months	0	1	0.0	1.4
9 months	0	1	0.1	1.6

Source: Pushpamma *et al.*, 1985.

Studies conducted in Senegal showed that when properly dried and threshed sorghum and millets were mixed with 30 percent sand, storage losses were reduced.

Pushpamma *et al.* (1985) found in India that the storage loss of sorghum over seven months was greater than that of pearl millet, which was in turn greater than that of finger millet (Table 14). They also found that the moisture content of all the stored grains increased and the levels of niacin and protein fell (Table 15). Rao and Vimla (1993) showed that pretreatment of sorghum grain with 2 percent tricalcium phosphate reduced the development of rancidity during storage.

The influence of seed moisture (relative humidity), temperature and the surrounding atmosphere on sorghum germination was studied by Bass and Stanwood (1978). Sorghum seeds were stored in sealed metal cans in six

TABLE 15

Chemical composition of sorghum and millets stored for different periods (moisture-free basis)

Storage period	Number of samples	Moisture (%)	Protein (g)	Non-protein nitrogen (mg)	Thiamine (mg)	Riboflavin (mg)	Niacin (mg)
Sorghum							
1 month	26	10.4	8.5	326	0.32	0.18	2.3
5 months	26	10.4 (0)	8.2 (-3.5)	240 (+1.7)	0.31 (-3.1)	0.16 (-11.1)	2.1 (-8.7)
9 months	22	11.1 (+6.7)	7.6 (-10.6)	246 (+4.3)	0.24 (-25.1)	0.16 (-11.1)	2.0 (-13.0)
Pearl millet							
1 month	18	9.3	10.0	282	0.33	0.21	2.4
5 months	18	11.0 (+18.3)	9.9 (-1.0)	285 (+1.1)	0.29 (-12.1)	0.21 (0)	2.4 (0)
9 months	12	10.7 (+15.1)	8.9 (-11.0)	297 (+5.3)	0.20 (-39.4)	0.21 (0)	2.0 (-16.7)
Finger millet							
1 month	7	10.9	7.6	193	0.37	0.19	1.3
5 months	7	10.9 (0)	7.4 (-2.6)	216 (+12.0)	0.33 (-10.8)	0.18 (-5.3)	1.3 (0)
9 months	7	11.6 (+6.4)	7.2 (-5.3)	275 (+42.5)	0.21 (-43.2)	0.17 (-10.5)	1.1 (-15.4)

Note: Figures in parentheses indicate percentage decrease (-) or increase (+) from the values at the initial (one-month) sampling.

Source: Pushpamma *et al.*, 1985.

different atmospheric conditions (air, nitrogen, carbon dioxide, helium, argon and a vacuum) at three different moisture levels and at five different temperatures over a 16-month period. Temperature was the only parameter that affected the rate of germination, which was lowest at -12°C.

Methods used for storing grains are influenced by the value of the crop, the quantity stored and environmental conditions. Compared to other cereal crops, sorghum and millets are not widely traded internationally, and within those developing countries where they are grown for human food there is usually a balance between local production and local demand. Farmers and

rural householders in developing countries store most of what is grown in small storage structures. There is not much need for bulk storage of these crops.

Storage containers vary from small traditional on-farm or domestic containers to silos which are sometimes found on large farms. In many countries, small granaries are made by weaving plant materials such as bamboo, stalks, bark and small branches and then sealing any gaps with mud or dung. These structures may be built directly on the ground or raised off the ground on platforms or stilts.

Storage practices in Africa

In some countries in West Africa sorghum and millet grains are mixed with wood ash and stored in clay pots (Vogel and Graham, 1979). In Nigeria sorghum and millets are stored as unthreshed heads in a solid walled container called a *rumbu*. For short-term storage, bundles of sorghum and millet heads are arranged in layers in the *rumbu*. For long-term storage of three to six years, the heads are laid out individually rather than in bundles. Some farmers spread the leaves of *gwander daji* (*Annona senegalensis*) on the bottom of the *rumbu* and between each layer of grain. When a *rumbu* is full, the mouth is sealed with clay.

In Uganda, sorghum is threshed and stored in gunny sacks, whereas millets are stored unthreshed. In the Sudan, pits holding 2 to 5 tonnes of grain are used as underground stores.

Storage practices in India

Most of the sorghum and millets grown in Andhra Pradesh are grown for personal consumption. Pushpamma and Chittemma Rao (1981) described the various ways these grains are stored there. Occasionally sorghum and millets are stored on the ground, usually unthreshed. The earheads are heaped in a pile (either indoors or outdoors) and covered with straw. As the grain is needed, earheads are removed and threshed. More often, grain is stored in gunny sacks, which are stacked either on the floor or on raised wooden platforms. Underground pits, which may be located underneath the house or outside, are also used. The pit is lined with paddy straw or sorghum

straw. When it is full of grain the grain is covered with straw and soil. For longer-term storage, the top is plastered over with mud. Storage jars, silos and bins are made from a number of different materials. On the smallest scale, grain is stored in clay pots. Larger containers are made from wood, brick or stone or from bamboo made into a basket which is then sealed with clay or dung. When these containers are kept indoors they are sometimes left uncovered, but when they are kept outdoors they are covered with either a lid or a thatched roof. If the grain is to be stored for a long time, the top of the bin is plastered over with mud or dung. Occasional exposure to sunshine is the most commonly used measure for preventing insect infestation.

Storage of flour

Flour is usually produced as it is needed and is not often stored for long periods because it tends to turn rancid. This is particularly evident with pearl millet flour, because of its very high fat content. Sorghum and millets, particularly pearl millet, are therefore best stored as whole grain.

TRADITIONAL PROCESSING METHODS

Processing untreated grains

Flour made by grinding whole grain is occasionally used, particularly with the smaller millets, but in most places where sorghum and millets are consumed the grain is partially separated into its constituents before food is prepared from it.

The first objective of processing is usually to remove some of the hull or bran – the fibrous outer layers of the grain. This is usually done by pounding followed by winnowing or sieving. The grain may first be moistened with about 10 percent water or soaked overnight. When hard grains are pounded, the endosperm remains relatively intact and can be separated from the heavy grits by winnowing. With soft grains, the endosperm breaks into small particles and the pericarp can be separated by winnowing and screening.

When suitably prepared grain is pounded, the bran fraction contains most of the pericarp, along with some germ and endosperm. This fraction is usually fed to domestic animals. The other fraction, containing most of the endosperm and much of the germ along with some pericarp, is retained for

human consumption. Retaining the germ in the flour will improve aspects of its nutritional quality, but at the same time it will increase the rate at which the flour will become rancid. This is particularly important in the case of pearl millet.

Dry, moistened or wet grain is normally pounded with a wooden pestle in a wooden or stone mortar. Moistening the grain by adding about 10 percent water facilitates not only the removal of the fibrous bran, but also separation of the germ and the endosperm, if desired. Although this practice produces a slightly moist flour, many people temper the grain in this way before they pound it. Pounding moist or dry grain by hand is very laborious, time consuming and inefficient. A woman working hard with a pestle and mortar can at best only decorticate 1.5 kg per hour (Perten, 1983). Pounding gives a non-uniform product that has poor keeping qualities.

Many pearl millet grains have an irregular indentation in the pericarp. This makes it more difficult to decorticate pearl millet than it is to decorticate most other cereal grains (Kent, 1983).

The particle size of the endosperm fraction can be reduced by crushing or grinding to produce coarse grits or fine flour. This unpleasantly hard work is almost always done by women. Traditional grinding stones used to grind whole or decorticated grain to flour usually consist of a small stone which is held in the hand and a larger flat stone which is placed on the ground (Subramanian and Jambunathan, 1980; Vogel and Graham, 1979). Grain, which should be fairly dry, is crushed and pulverized by the backward and forward movement of the hand-held stone on the lower stone. The work is very laborious, and it is hard work for anyone to grind more than 2 kg of flour in an hour. In a traditional process used in many countries of Africa and Asia, decorticated grain is crushed to a coarse flour either with a pestle and mortar or between stones. Grain is also ground to coarse or fine flour in mechanized disk mills now located in many villages.

In wet milling, the sorghum or millet is soaked in water overnight (and sometimes longer) and then ground to a batter by hand, often between two stones. Soaking makes the endosperm very soft and the pericarp quite tough and makes grinding much easier, but it gives a batter or paste instead of flour.

Processing malted grains

Malting involves germinating grain and allowing it to sprout. Typically the grain is soaked for 16 to 24 hours, which allows it to absorb sufficient moisture for germination and for sprouts to appear. However, germinated sorghum rootlets and sprouts contain very large amounts of dhurrin, a cyanogenic glucoside, which on hydrolysis produces a potent toxin variously known as prussic acid, hydrocyanic acid (HCN) and cyanide (Panasiuk and Bills, 1984). The fresh shoots and rootlets of germinated sorghum and their extracts must therefore *never* be consumed, either by people or by animals, except in very small quantities (e.g. when the germinated grain is used just as a source of enzymes). Dada and Dendy (1988) showed that the removal of shoots and roots and subsequent processing reduced the HCN content by more than 90 percent.

Malted sorghum has traditionally been used in several countries in Africa, but always after careful removal of the toxic parts. *Hullu-murr* is an important traditional food prepared from malted sorghum in the Sudan (Bureng, Badi and Monawar, 1987). Alcoholic beverages and dumplings are prepared in Kenya from germinated sorghum and millet.

In the germination process, the grain produces α -amylase, an enzyme that converts insoluble starch to soluble sugars. This has the effect of thinning paste made by heating a slurry of starch in water, in turn allowing a higher caloric density in paste of a given viscosity, since as much as three times more flour can be used when the grain has been germinated. The energy that young children can consume is often limited by the bulk that they can consume. Thus using germinated grain can make food more suitable for certain categories of young children. Flour from malted grain is consequently used quite widely in the production of children's food, but when such foods are made from sorghum, great care must always be taken to ensure that the level of cyanide is adequately low, as children are particularly vulnerable to cyanide.

In India, malted finger millet is common and is considered to be superior to malted sorghum and malted maize. Studies have shown that finger millet develops higher amylase activity than sorghum and other millets (Seenappa, 1988). Germination of grain is reported to change the amino acid composi-

tion, convert starch into sugars and improve the availability of fat, vitamins and minerals.

Pal, Wagle and Sheorain (1976) measured the changes in the constituents of sorghum and various millets (finger, pearl, proso, kodo and barnyard) during malting. The malting losses for finger millet and foxtail millet were high. Pearl millet had the highest α -amylase activity. Amylolytic and proteolytic enzyme levels in malted pearl millet were comparable to those in malted barley.

The use of only 5 percent malted sorghum or finger millet was found to reduce the viscosity of weaning foods (Mosha and Svanberg, 1983; Seenappa, 1988).

Processing grain treated with alkali

To produce a particular type of tortilla that is popular in Mexico, sorghum grains are cooked in lime water for a short time and steeped overnight, washed to remove the excess alkali and then ground to a paste (Rizley and Suter, 1977).

Wood ash is used in traditional treatments to reduce the level of tannin in brown sorghums and improve the nutritional quality. Muindi and Thomke (1981) reported the use of wood ash in the United Republic of Tanzania. Mukuru (1992) described a tannin-reducing technique used in parts of eastern and central Africa where, because of grain-eating birds, only "high-tannin" sorghums are grown. The sorghum is first soaked overnight in a slurry of wood ash in water. After draining, it is left for three or four days to germinate. The germinated grains are sun-dried and pounded to loosen the adhering wood ash and to remove the sprouts, with their high levels of cyanide. The grain is then ground and used to prepare either a non-alcoholic beverage called *obushara* or an alcoholic drink containing about 3 percent alcohol called *omuramba*.

Processing parboiled grain

Parboiling is reported to help in dehusking kodo millet (Shrestha, 1972) and to eliminate the stickiness in cooked finger millet porridge (Desikachar, 1975).

INDUSTRIAL PROCESSING

While there are many machines available for processing hard white sorghum, there is unfortunately no well-proven industrial process available that is entirely satisfactory for making white products from coloured sorghums and millets.

Cereal grains can be milled wet, in the form of a thin aqueous slurry, usually to produce starch, or in an essentially dry form (often suitably dampened or "tempered") which usually produces meal (coarse or fine flour). A factory in Texas, United States, for wet milling sorghum operated intermittently from the 1940s to the 1970s (Rooney, 1992) but is now closed. No millets have ever been wet milled commercially to produce starch. The following technologies are all for dry and semi-wet milling.

In industrial processing, once the grain has been cleaned, the first operation is usually the separation of offal (the portion not normally used for human consumption) from the edible portion. The offal consists of the pericarp and sometimes the germ. Offal removal is frequently called decortication or dehulling.

Following the removal of offal, the edible portion is often milled to reduce the particle size of the edible fraction. There is usually a choice of techniques and mills that may be used for particle size reduction if a finer product is desired. Some of the earliest research and development work on milling

Grain dehuller



technology for pearl millet and sorghum was promoted by FAO in 1964, initially on a laboratory scale in Senegal and later on a semi-industrial scale in the Sudan. The conclusion was reached that the technology for milling wheat is not optimal for milling sorghum and millet (Perten, 1977).

Most industrial operations that can be carried out on untreated grain can also be used with grain that has been prepared in some way, for example grain that has been germinated and then suitably dried.

Three types of processors can be used to mill sorghum and millets on a commercial scale: abrasive decorticators, which abrade the pericarp away, i.e. progressively remove offal from the outside; machines that rub (rather than abrade) the pericarp off the endosperm; and roller mills, which cut the endosperm from the inside of the pericarp.

Abrasive decortication

Abrasive decorticators work by abrading away the fibrous pericarp. Obviously, the outer layers of the seed-coat are abraded away first and the innermost layers, which in many varieties contain those factors that most need to be removed, are the last to be abraded away. If all parts of all grains could be abraded away at the same rate, abrasive decortication would be an efficient way of removing the pericarp. However, different parts of individual grains are abraded away at very different rates, and there is some loss of endosperm (particularly from damaged grains) even when the grain is only lightly abraded. Also, non-spherical seeds, e.g. pearl millet grains, tend to abrade away much more quickly at some points than at others.

When hard white sorghum grains, uncontaminated with seeds with a red testa, are decorticated in an abrasive decorticator, any pericarp left on the grain is hard to see, and when the pearled grain is milled, the presence of pericarp goes largely unnoticed. However, the ability of abrasive decorticators to produce an adequately white product falls sharply with increasing levels of contamination from seeds with a coloured seed-coat. When the contaminating seeds have a red testa (which is deeply coloured and is practically the last layer to be abraded away) a decorticator's ability to produce an acceptably white product falls even more sharply. The problem is compounded by the fact that many contaminating seeds are comparatively

soft and their exposed endosperm is ground away quickly. As a result, milling yields often fall to unacceptably low levels.

Decorticators produce what is visually a very acceptable product in a good yield from grain well suited to abrasive decortication. However, if the grain to be ground is not always going to consist of a very high proportion of hard, white, spherical seeds of fairly regular size, a very careful analysis of the economics of operating an abrasive decorticator should be made on the basis of recovery rates derived from trial runs.

Even though decorticators are well suited to small-scale operations, these machines have often proved to be too large for the system into which they were introduced. In many cases they have been introduced less successfully than originally hoped, either because of a lack of supplies of the high-quality grain that is needed for them to work properly or because of insufficient local demand for the product. Very small units are likely to be run less efficiently than larger ones.

Most decorticators are based on a prototype put out by the Prairie Regional Laboratory (PRL) in Canada. This type of decorticator has the enormous advantages of being relatively inexpensive to install and relatively simple to maintain and operate. Bassey and Schmidt (1989) described the development of this type of decorticator and its use in Africa. More recently it has been introduced in India.

In 1976, a prototype decorticator was established in Maiduguri, Nigeria. A larger unit to process 5 to 10 tonnes of sorghum per day was installed at Pitsane in southern Botswana in 1978 but the demand for the product was inadequate to keep the equipment running at full capacity. The Centre national de recherches agronomiques (CNRA) in Bambe, Senegal, began to use a PRL decorticator to decorticate sorghum and millet in 1979. The capacity of this decorticator also exceeded the demand for the product.

FAO supplied the Food Research Centre (FRC) in the Sudan with a pilot plant including a decorticator manufactured in Germany after FRC had compared decorticators made by several different manufacturers. FRC is currently decorticating white sorghum for a local urban market. The centre has also produced pearled sorghum as a substitute for rice (Badi, Perten and Abert, 1980); although the product has to be cooked much longer than rice,

it was well accepted. Of the five most popular varieties of sorghum grown in the Sudan, two (Feterita and Mayo) are unsuitable for abrasive decortication.

James and Nyambati (1987) described the industrial preparation of pearly brown and white sorghum in Kenya using a decorticating machine that could mill sorghum in batches or continuously, but they found it was difficult to obtain sufficient sorghum suitable for processing. The product was sold at 60 percent of the price of rice and consumer acceptance was very good. Flour was also produced from the pearly grain.

Various modifications have been made to the PRL design to suit specific conditions. A variant of the PRL decorticating machine was developed in the early 1980s by Palyi and tested in Canada. The Palyi-Hanson BR 001-2 can mill 3 tonnes per hour. Under local management in the Gambia a PRL decorticating machine processed 50 tonnes of pearl millet over a one-year test period, after which modifications were made to the design. In 1986 the Rural Industrial Innovation Centre (RIIC) introduced a modification that enabled the machine to handle small quantities of grain (Bassey and Schmidt, 1989). By 1989, about 35 RIIC decorticating machines had been installed in Botswana, but for one reason or another, not all of these machines are still being used for milling sorghum or millet. In turn, local agencies in some of the main countries to which the RIIC design has been exported (e.g. Zimbabwe, Senegal) have deemed it necessary to modify the RIIC design for improved operation for local grain.

In Zimbabwe, decorticating machines were placed in five rural locations for evaluation. A local research group, Environment Development Activities, produced a modified version that can process one tonne of grain in eight hours. In Senegal, a local modification was evaluated in ten villages. Decorticating machines based on a second local design (called the mini-SISMAR/ISRA), which can mill about 600 kg of grain in eight hours, were then introduced.

Equipment of RIIC design was introduced at Morogoro, United Republic of Tanzania, in 1982. Although the first unit was unsuccessful, four pilot systems were established locally for evaluation. In 1982, a mill with an RIIC decorticating machine was established in Ethiopia, but the supplies of grain for it were inadequate because of the drought.

There has also been an intensive effort to introduce RIIC decorticators in Andhra Pradesh. Decortication improved the quality of the flour from sorghum and millets so that it could be used in new ways (Geervani and Vimala, 1993).

High-yielding sorghums introduced in Mali were soft and could not be decorticated in PRL-type decorticators (Scheuring *et al.*, 1983).

A number of large decorticators have been installed around the world with capacity ranging from 1 to 2.5 tonnes per hour. Typically, they are vertical axis units with abrasive disks that have been carefully selected for the optimal degree of abrasion. The grain is first cleaned to separate sand, dust, coarse material and other impurities. An aspirator removes the abraded bran through a screen. The bran is sometimes further separated into fine bran (mostly pericarp) and a mixture of germ, broken grain and coarse bran. A 1-t/hour decorticator manufactured in Switzerland was run for several years in Zimbabwe, preparing coarse sorghum flour that was introduced into a wheat flour mill. A 2.5-t/hour unit manufactured in Germany was installed in the Sudan. Other large units are reportedly in operation in Nigeria. As with small units, high-quality sorghum is needed to produce an acceptably white product in these larger decorticators. Sufficient quantities of high-quality sorghum to keep large mills running at full capacity are not often available.

Rubbing techniques

Munck, Bach Knudsen and Axtell (1982) described a new industrial milling process developed in Denmark, which does not involve abrasive milling. Decortication is achieved by a steel rotor rotating the grain mass within a generally cylindrical chamber. When the grain is properly tempered, the pericarp is rubbed off by the movement of one seed against another. However, when the grain is too dry, as was the case in a factory in the Sudan, abrasion of the internal components of the mill becomes severe. The hulls and the endosperm fragments are separated in a cyclone and the endosperm particles are milled in a proprietary mill. These units have a capacity of 2 tonnes of sorghum per hour. The system was reported to yield 80 percent flour with whiteness comparable to traditional milling, but to do this it

requires grain with specifications similar to those required for efficient abrasive decortication.

Roller mills

Most wheat is milled in a type of mill called a roller mill. Roller mills are the most efficient mills for separating the constituents of cereals. Two types of rollers are used: rollers with axial grooves, which cut the endosperm from the pericarp (effectively cutting it away from the inside), and smooth rollers, which progressively crush the endosperm pieces into finer and finer flour. Normally the grain is passed through a number of roller mills, often 20 or more. Wheat milling technology is suitable for milling large quantities of grain, but it requires a large investment and experience in operating and maintaining the equipment. For all these reasons, it is therefore not suitable for milling sorghum and millets in very small-scale operations. However, roller mills are very efficient in separating the edible portion of cereals from the offal and can do so with sorghum and millets regardless of the physical characteristics of the grain: it does not matter if the grain is soft, coloured or broken. Roller milling might therefore have a place where high-quality products are required from comparatively large quantities of grain of poor or indifferent quality, particularly where there is spare capacity in an existing wheat mill.

To withstand the stresses of roller milling, the pericarp of sorghum and millets has to be much moister than that of wheat. Early efforts to roller-mill sorghum and millets always ended in failure because the grain was dry when it was milled. It would shatter, the pericarp breaking into small pieces that were too brittle to allow separation of the endosperm. Using conventional tempering techniques, Perten (1983) was unable to achieve efficient separation of the offal of either sorghum or millets from the endosperm. He concluded that sorghum and millets are more difficult to grind than wheat and that they produce a coarser and much darker flour which contains high levels of fat and ash.

The use of moisture levels much higher than those used for milling wheat was first reported by Abdelrahman, Hoseney and Varriano-Marston (1983) for milling pearl millet and by Cecil (1986, 1992) for milling other millets

and sorghum. The term semi-wet milling was adopted for this technique. For millets, about 10 percent water must be equilibrated in the grain for four hours before it is ready for milling; for sorghum, about 20 percent moisture must be added and the grain conditioned for six hours. The damp material flows almost as easily as normally tempered wheat products do, and no hold-up problems were encountered in several hours of running 2 tonnes per hour of red sorghum in a commercial mill. In early experiments, comparatively low yields of fine flour were obtained, but subsequent work produced low-fibre, low-tannin grits from red sorghum in a commercial mill with six roller passes with a yield of 72 percent (compared with typical wheat recovery of 70 percent). In a laboratory mill with three milling passes, 84 percent yield of grits was obtained from commercial white sorghum from Botswana and 83 percent from white sorghum from Lesotho. All the grits contained very low levels of fibre.

Semi-wet milling has several advantages, including the excellent separation of the offal from the edible portion and the opportunity for using well-tested existing commercial wheat-milling equipment without the need for any changes in the set-up of the mills. White flour with practically no tannin, which tastes better, looks better and is nutritionally better than flour that contains tannin, can be produced from high-tannin coloured varieties. Mixtures of sorghum or millet varieties, soft varieties, misshapen seeds and mixtures of sorghum with other grains (including wheat) can all be milled together if necessary. Moistening the endosperm softens it to such an extent that very little energy is needed to mill it. Semi-wet milling of pearl millet, unlike abrasive decortication, may also help eliminate substances that cause goitre (Klopfenstein, Leipold and Cecil, 1991).

Redundant or underutilized wheat mills can be used with minimal additions and the mill can be reverted to milling wheat within a few minutes. Alternatively, any type of sorghum can be milled together with wheat. For a period of about five days, 0.6 tonnes of red sorghum and 14 tonnes of wheat per hour were milled together without difficulty in a commercial mill in Zimbabwe.

Semi-wet milling has some disadvantages. Although it would not be difficult or very expensive in a commercial system to dry the products of

semi-wet milling, they are usually too damp for long-term storage. In semi-wet milling, microbiological growth might be more vigorous than in conventional milling of wheat, but reasonable attention to hygiene will minimize this problem. Semi-wet milling is not suitable for very small operations. Finally, although it has been shown that sorghum can be milled semi-wet without any difficulty in commercial equipment, the technique has not yet been proved over an extended period of operation.

Size reduction

Many mills can be used to reduce the size of the particles obtained by decortication, but the type that is usually used (and is also probably the simplest to use and the cheapest to install) is the hammer mill. Hammer mills are available in all sizes. They consist of blunt blades rotating rapidly in an enclosed cylinder with an outlet covered by a screen. The size of the holes in the screen determines the size of the particles of flour, but small holes will reduce the throughput of the mill, and if they are too small overheating may result.

If roller mills are used for separating the endosperm from the offal, the particle size is usually reduced in roller mills with smooth rollers.

Chapter 4

Chemical composition and nutritive value

The composition of the kernel fractions of sorghum and pearl millet is given in Table 16. The sorghum bran is low in protein and ash and rich in fibre components. The germ fraction in sorghum is rich in ash, protein and oil but very poor in starch. Over 68 percent of the total mineral matter and 75 percent of the oil of the whole kernel is located in the germ fraction. Its contribution to the kernel protein is only 15 percent. Sorghum germ is also rich in B-complex vitamins. Endosperm, the largest part of the kernel, is relatively poor in mineral matter, ash and oil content. It is, however, a major contributor to the kernel's protein (80 percent), starch (94 percent) and B-complex vitamins (50 to 75 percent).

The pearl millet bran is low in mineral matter like that of sorghum, but it is remarkably rich in protein (17.1 percent). The germ fraction in pearl millet is relatively large, 16 percent as against 10 percent in sorghum. It is also rich in oil (32 percent), protein (19 percent) and ash (10.4 percent). Practically all the oil (87 percent) of the whole kernel is in the germ fraction, which also accounts for over 72 percent of the total mineral matter. Greater concentration of minerals in the germ and the bran layers than in endosperm is typical of cereal grains (MacMasters, Hinton and Bradbury, 1971). The total fat content of pearl millet is higher than that of other millets and sorghum because of the size of the germ and its high oil content and because of somewhat higher levels of fat in the bran fraction.

VARIATION IN GRAIN COMPOSITION

Like other cereals, sorghum and millets are predominantly starchy. The protein content is nearly equal among these grains and is comparable to that

TABLE 16
Nutrient content of whole kernel and its fractions^a

Kernel fraction	% of kernel weight	Protein ^b (%)	Ash (%)	Oil (%)	Starch (%)	Calcium (mg/kg)	Phosphorus (mg/kg)	Niacin (mg/100 g)	Riboflavin (mg/100 g)	Pyridoxin (mg/100 g)
Sorghum										
Whole kernel	100	12.3	1.67	3.6	73.8			4.5	0.13	0.47
Endosperm	82.3	12.3 (80)	0.37 (20)	0.6 (13)	82.5 (94)			4.4 (76)	0.09 (50)	0.40 (76)
Germ	9.8	18.9 (15)	10.4 (69)	28.1 (76)	13.4 (20)			8.1 (17)	0.39 (28)	0.72 (16)
Bran	7.9	6.7 (4.3)	2.0 (11)	4.9 (11)	34.6 (4)			4.4 (7)	0.40 (22)	0.44 (8)
Pearl millet										
Whole kernel	100	13.3	1.7	6.3				55	358	
Endosperm	75	10.9 (61)	0.32 (14)	0.53 (6)				17 (25)	240 (56)	
Germ	17	24.5 (31)	7.2 (71)	32.2 (87)						
Bran	8	17.1 (10)	3.2 (15)	5.0 (6)				168 (36)	442 (15)	

^a Values in parentheses represent percentage of whole kernel value.

^b N × 6.25.

Sources: Hubbard, Hall and Earle, 1950 (sorghum); Abdelrahman, Hosseiny and Varriano-Marston, 1984 (pearl millet).

of wheat and maize (Table 17). Pearl and little millet are higher in fat, while finger millet contains the lowest fat. Barnyard millet has the lowest carbohydrate content and energy value. One of the characteristic features of the grain composition of millets is their high ash content. They are also relatively rich in iron and phosphorus. Finger millet has the highest calcium content among all the foodgrains. High fibre content and poor digestibility of nutrients are other characteristic features of sorghum and millet grains, which severely influence their consumer acceptability. Generally the whole grains are important sources of B-complex vitamins, which are mainly concentrated in the outer bran layers of the grain.

Sorghum and millets do not contain vitamin A, although certain yellow-endosperm varieties contain small amounts of β -carotene, a precursor of vitamin A. No vitamin C is present in the raw millet grains.

Considerable variation in the grain composition of these cereals has been reported, particularly for sorghum and pearl millet (Hulse, Laing and Pearson, 1980; Jambunathan and Subramanian, 1988; Rooney and Serna-Saldivar, 1991) (Table 18). Genetic factors play a major part in determining grain composition. Environmental factors also have a role. In several cereal grains, including sorghum, an inverse correlation has been observed between grain yield and protein content (Frey, 1977). The protein content of the grain is also significantly and inversely correlated with its weight and starch content. On the other hand, the ash content and protein content of the sorghum grain are positively correlated with each other (Subramanian and Jambunathan, 1982).

Goswamy and co-workers (Goswamy, Sehgal and Sharma, 1969; Goswamy, Sharma and Gupta, 1969; Goswamy, Sehgal and Gupta, 1970; Goswamy, Sharma and Sehgal, 1970) analysed a number of pearl millet varieties of African, American and Indian origin and observed that variations in protein, fat, total ash, calcium, phosphorus and iron were large but were similar in the three types. Singh *et al.* (1987) compared the grain composition of five pearl millet varieties, of which three were inbred lines with high protein content (14.4 to 19.8 percent) and two were normal-protein (9.9 to 11.3 percent) cultivars. In the five genotypes, the values for fat, crude fibre, total ash and starch content were within the normal ranges

TABLE 17
Nutrient composition of sorghum, millets and other cereals (per 100 g edible portion; 12 percent moisture)

Food	Protein ^a (g)	Fat (g)	Ash (g)	Crude fibre (g)	Carbohydrate (g)	Energy (kcal)	Ca (mg)	Fe (mg)	Thiamin (mg)	Riboflavin (mg)	Niacin (mg)
Rice (brown)	7.9	2.7	1.3	1.0	76.0	362	33	1.8	0.41	0.04	4.3
Wheat	11.6	2.0	1.6	2.0	71.0	348	30	3.5	0.41	0.10	5.1
Maize	9.2	4.6	1.2	2.8	73.0	358	26	2.7	0.38	0.20	3.6
Sorghum	10.4	3.1	1.6	2.0	70.7	329	25	5.4	0.38	0.15	4.3
Pearl millet	11.8	4.8	2.2	2.3	67.0	363	42	11.0	0.38	0.21	2.8
Finger millet	7.7	1.5	2.6	3.6	72.6	336	350	3.9	0.42	0.19	1.1
Foxtail millet	11.2	4.0	3.3	6.7	63.2	351	31	2.8	0.59	0.11	3.2
Common millet	12.5	3.5	3.1	5.2	63.8	364	8	2.9	0.41	0.28	4.5
Little millet	9.7	5.2	5.4	7.6	60.9	329	17	9.3	0.30	0.09	3.2
Barnyard millet	11.0	3.9	4.5	13.6	55.0	300	22	18.6	0.33	0.10	4.2
Kodo millet	9.8	3.6	3.3	5.2	66.6	353	35	1.7	0.15	0.09	2.0

^a N × 6.25.
 Sources: Hulse, Laing and Pearson, 1980; United States National Research Council/National Academy of Sciences, 1982; USDA/HNIS, 1984.

TABLE 18
Chemical composition of sorghum and pearl millet genotypes from the world germplasm collection at ICRISAT^a

Food	Protein (%)	Fat (%)	Ash (%)	Crude fibre (%)	Starch (%)	Amylose (%)	Soluble sugar (%)	Reducing sugar (%)	Calcium (mg/100 g)	Phosphorus (mg/100 g)	Iron (mg/100 g)
Sorghum											
No. of genotypes	10 479	160	160	100	160	80	160	80	99	99	99
Low	4.4	2.1	1.3	1.0	55.6	21.2	0.7	0.05	6	388	4.7
High	21.1	7.6	3.3	3.4	75.2	30.2	4.2	0.53	53	756	14.1
Mean	11.4	3.3	1.9	1.9	69.5	26.9	1.2	0.12	26	526	8.5
Pearl millet											
No. of genotypes	20 704	36	36	36	44	44	36	16	27	27	27
Low	5.8	4.1	1.1	1.1	62.8	21.9	1.4	0.10	13	185	4.0
High	20.9	6.4	2.5	1.8	70.5	28.8	2.6	0.26	52	363	58.1
Mean	10.6	5.1	1.9	1.3	66.7	25.9	2.1	0.17	38	260	16.9

^aAll values except protein are expressed on a dry-weight basis.

Source: Jayanthan and Subramanian, 1988.

as reported by Goswamy and co-workers and others (Jambunathan and Subramanian, 1988). Further, the high-protein lines contained 60 percent more protein than the normal varieties but had 40 percent less carbohydrate and 20 percent less fat. The high-protein lines were also high in fibre.

Differences in grain composition in genotypes of other millets have also been reported. In finger millet, the value ranges reported by Pore and Magar (1977) are protein, 5.8 to 12.8 percent; fat, 1.3 to 2.7 percent; total ash, 2.1 to 3.7 percent; and carbohydrate 81.3 to 89.4 percent. Variations in the mineral content of these varieties were also large. Differences in the protein and mineral composition of finger millet hybrids have also been reported by Babu, Ramana and Radhakrishnan (1987). In foxtail millet from the world germplasm collection the protein content ranged from 6.7 to 15 percent and the ash content from 2.06 to 4.81 percent (Dhindsa, Dhillon and Sood, 1982). Monteiro *et al.* (1988) observed similar variations in protein (11.1 to 15 percent), ash (1.1 to 1.6 percent), fat (4.7 to 6.3 percent) and carbohydrate (65 to 75.7 percent) in 12 cultivars of foxtail millet.

Environmental factors including agronomic practices affect grain composition. Grain protein and its amino acid composition in sorghum differ with the location at which the crop is grown (Deosthale and Mohan, 1970; Deosthale, Nagarajan and Visweswar Rao, 1972; Deyoe and Shellenberger, 1965). The level of nitrogen fertilizer also influences the quantity and quality of protein in sorghum (Deosthale, Nagarajan and Visweswar Rao, 1972; Waggle, Deyoe and Smith, 1967) and also in pearl millet (Deosthale, Visweswar Rao and Pant, 1972; Shah and Mehta, 1959). Warsi and Wright (1973) noted that application of nitrogen fertilizer increased the grain yield and protein. Higher protein in response to fertilizer nitrogen was mainly the result of increased accumulation of prolamin, a poor-quality protein, in the grain (Sawhney and Naik, 1969). The level of nitrogen fertilizer had no effect on the mineral composition of grain sorghum. However, the mineral content of the sorghum increased with increasing levels of phosphorus fertilizer (Deosthale, Nagarajan and Visweswar Rao, 1972). The mineral composition of sorghum grain was influenced more by location than by variety (Deosthale and Belavady, 1978). Other factors such as the

density of the plant population, season, water and stress also contribute to variations in grain composition.

CARBOHYDRATE

Starch is the major storage form of carbohydrate in sorghum and millets. It consists of amylopectin, a branched-chain polymer of glucose, and amylose, a straight-chain polymer.

The digestibility of the starch, which depends on hydrolysis by pancreatic enzymes, determines the available energy content of cereal grain. Processing of the grain by methods such as steaming, pressure-cooking, flaking, puffing or micronization of the starch increases the digestibility of sorghum starch. This has been attributed to a release of starch granules from the protein matrix rendering them more susceptible to enzymatic digestion (McNeill *et al.*, 1975; Harbers, 1975).

The physico-chemical properties of the starch affect the textural characteristics of the food preparations made from grain. The behaviour of starch in water is temperature and concentration dependent (Whistler and Paschall, 1967). Grain starches in general show very little uptake of water at room temperature, and their swelling power is also small. At higher temperature water uptake increases and starch granules collapse, which leads to solubilization of amylose and amylopectin to form a colloidal solution. This is the gelatinization stage. Genetic and environmental factors affect the gelatinization temperature of grain starch (Freeman, Kramer and Watson, 1968). Heat treatment of starch in a limited amount of water leads to swelling of the granules with very little loss of soluble material and partial gelatinization of the starch.

On cooking, the gelatinized starch tends to return from the soluble, dispersed and amorphous state to an insoluble crystalline state. This phenomenon is known as retrogradation or setback; it is enhanced with low temperature and high concentration of starch. Amylose, the linear component of the starch, is more susceptible to retrogradation. Some characteristics of sorghum and millet starches are presented in Table 19; soluble sugar composition and total sugar content are given in Table 20.

TABLE 19
Characteristics of isolated starches of sorghum and millets

Grain	Amylose (%)	Gelatinization temperature (°C)		Water- binding capacity (%)	Swelling at 90°C (%)	Solubility at 90°C (%)	Viscosity (anerograph-Briabender units)		
		Initial	Final				At 03°-95°C	After holding at 95°C	Cooled to 35° or 50°C
Sorghum	24.0	68.5	75.0	105	22	22	600	400	580
Sorghum (waxy)	1.0	67.5	74.0	—	49	19	380	290	390
Pearl millet	21.1	61.1	68.7	87.5	13.1	9.16	460	396	568
Proso millet	28.2	56.1	61.2	108.0	12.0	6.89	688	520	826
Foxtail millet (a)	—	53.5	59.5	128.5	11.2	4.65	840	620	1 100
Foxtail millet (b)	17.5	55.0	62.0	—	9.8	4.80	1 780	1 540	2 000
Kodo millet	24.0	57.0	68.0	—	12.0	5.50	300 ^a	270	390
Finger millet	16.0	64.3	68.3	—	11.4	6.50	1 633	1 286	1 796

^aPeak viscosity achieved at 83.5°C.

Sources: Rooney and Serna-Saldivar, 1991; Leach, 1965; Horan and Heider, 1946; Subramanian *et al.*, 1982; Beleja, Varriano-Marston and Hosney, 1980; Yanez and Walker, 1986; Lorenz and Hinze, 1976; Wankhede, Shehnaj and Raghuendra Rao, 1979; Paramadhan and Tarannath, 1980.

TABLE 20
Soluble sugar composition of sorghum and millets (g per 100 g, dry-matter basis)

Grain	Number of cultivars	Total sugar	Sucrose	Glucose + fructose	Raffinose	Stachyose
Sorghum, normal (a)	10	2.25 (1.3-5.2)	1.68 (0.9-3.9)	0.25 (0.06-0.74)	0.23 (0.10-0.39)	0.10 (0.04-0.21)
Sorghum, normal (b)	—	1.34	0.61	0.52	0.15	0.06
Sorghum, sugary	—	2.21	0.81	0.95	0.39	0.06
Sorghum, high lysine	—	2.57	0.94	1.13	0.39	0.11
Pearl millet	9	2.56 (2.16-2.78)	1.64 (1.32-1.82)	0.11 (0.08-0.16)	0.71 (0.65-0.84)	0.09 (0.06-0.13)
Finger millet	3	0.65 (0.59-0.69)	0.22 (0.20-0.24)	0.16 (0.14-0.19)	0.07 (0.06-0.08)	—
Foxtail millet	1	0.46	0.15	0.10	0.04	—
Proso millet	6	—	0.66	—	0.08	—

Sources: Subramanian, Jambunathan and Suryaprakash, 1980; Murty *et al.*, 1985; Subramanian, Jambunathan and Suryaprakash, 1981; Wankhede, Shehnaj and Raghavendra Rao, 1979a; Becker and Lorenz, 1978.

Sorghum

With values ranging from 56 to 73 percent, the average starch content of sorghum is 69.5 percent (Jambunathan and Subramanian, 1988). About 70 to 80 percent of the sorghum starch is amylopectin and the remaining 20 to 30 percent is amylose (Deatherage, McMasters and Rist, 1955). Both genetic and environmental factors affect the amylose content of sorghum (Ring, Akingbala and Rooney, 1982). Waxy or glutenous sorghum varieties are very low in amylose; their starch is practically 100 percent amylopectin (Ring, Akingbala and Rooney, 1982; Deatherage, McMasters and Rist, 1955). But in sugary sorghum the amylose content of the starch is about 5 to 15 percent higher than in normal sorghum (Singh and Axtell, 1973b). The total carbohydrate content of sugary sorghum is normal, however, since it contains exceptionally high levels of water-soluble polysaccharides (29.1 percent).

The digestibility of isolated starch of sorghum cultivars ranged from 33 to 48 percent as against 53 to 58 percent for corn starches (Sikabbubba, 1989). The texture of the grain endosperm, the particle size of the flour and starch digestibility were found to be strongly correlated with each other. Starch in floury sorghum was found to be more digestible than that in corneous sorghum. Particles of ground floury sorghum were smaller than those of similarly ground corneous sorghum. The smaller particle size and correspondingly greater surface area facilitate the enzyme action and thus improve starch digestibility.

The chemical nature of the starch, particularly the amylose and amylopectin content, is yet another factor that affects its digestibility. The starch digestibility was reported to be higher in low-amylase, i.e. waxy, sorghum than in normal sorghum, corn and pearl millet grains (Hibberd *et al.*, 1982). Feeding trials in rats (Elmalik *et al.*, 1986) and other animal species (Sherrod, Albin and Furr, 1969; Nishimuta, Sherrod and Furr, 1969) have confirmed the superiority of waxy sorghum over normal grain types in terms of dry matter and gross energy digestibility.

The presence of tannins in the grain contributes to the poor digestibility of starch in some varieties of sorghum (Dreher, Dreher and Berry, 1984). Tannins isolated from sorghum grain were shown to inhibit the enzyme

X-amyllose, and they also bind to grain starches to varying degrees (Davis and Hoseney, 1979).

The gelatinization temperature of isolated sorghum starch and that of finely ground flour of the corresponding endosperm has been reported to be the same. On the other hand the pasting temperature, i.e. the temperature at which starch attains peak viscosity when heated with water to form a paste, was found to be about 10°C higher for the sorghum flour than for the isolated starch.

The quality of cooked sorghum has been strongly associated with the total and soluble amylose content of the grain and also the soluble protein content (Cagampang and Kirleis, 1984). The swelling power of starch and its solubility significantly influenced the cooking quality of sorghum (Subramanian *et al.*, 1982). The percentage weight increase of cooked grain was negatively correlated with starch solubility at 60°C, a temperature at which most of the starch granules will have reached gelatinization stage. The swelling power of starch at 60° and 90°C and solubility at 25° and 50°C were inversely correlated with gruel solid content, which directly depended on the starch content of the grain. The starch gelatinization temperature did not show any significant effect on the cooking quality of sorghum.

Plasticity of sorghum flour dough mostly arises from the gelatinization of starch when the dough is prepared in hot or boiling water. The stickiness of the cooked flour is a function of the starch gelatinization. Porridge prepared from hard endosperm of sorghum is less sticky than that prepared from grains with a larger proportion of floury endosperm (Cagampang, Griffith and Kirleis, 1982).

Dough prepared with cold water has poor adhesiveness and is difficult to roll thin. Thus heat modification of the starch when the dough is prepared with hot water determines its rolling properties (Desikachar and Chandrashekhar, 1982). Higher water uptake, low gelatinization temperature, high peak paste viscosity and high setback are the starch properties that have been shown to be associated with good quality of *roti*, the unleavened bread that is the most common form in which sorghum and pearl millet are consumed on the Indian subcontinent. On the other hand, for stiff porridges such as Indian *mudde* or *sankhati* and African *tô*, the desirable characteristics of the

grain starch are high gelatinization temperature, low peak paste viscosity and low retrogradation tendency. In other words, the starch characteristics for good-quality *roti* were found to be exactly opposite to those desirable for good-quality porridge. Thus sorghum varieties that are not suitable for *roti* may be suitable for porridge. Almeida-Dominguez, Serna-Saldivar and Rooney (1991) found that low-amyllose or waxy sorghum produced sticky dough (*masa*) and was not suitable for preparation of tortillas.

Pearl millet

In different pearl millet genotypes the starch content of the grain varied from 62.8 to 70.5 percent, soluble sugar from 1.2 to 2.6 percent and amylose from 21.9 to 28.8 percent (Jambunathan and Subramanian, 1988). Lower values for starch (56.3 to 63.7 percent) and amylose (18.3 to 24.6 percent) have been found in some high-yielding Indian pearl millet varieties (Singh and Popli, 1973). Subramanian, Jambunathan and Suryaprakash (1981) found that the predominant component of total soluble sugar (2.16 to 2.78 percent) was sucrose (66 percent), followed by raffinose (28 percent). Other sugars detected in measurable amounts were stachyose, glucose and fructose. The proportion of sucrose in total sugar was lower in pearl millet than in sorghum.

Pasting properties of pearl millet starch were generally similar to those of sorghum except when it was held for one hour at 95°C (Badi, Hoseney and Finney, 1976). Beleia, Varriano-Marston and Hoseney (1980) considered inherent molecular dissimilarities the primary factor in physico-chemical differences among five pearl millet starches examined. The amylose content of these starches varied within a narrow range (22 to 24 percent). Variation in the water-binding capacity (83.6 to 99.5 percent) was probably due to differences in the proportions of amorphous and crystalline starch in the granule; amorphous starch has greater water absorption capacity than crystalline starch. In the five starches, the initial gelatinization temperature ranged from 59° to 63°C, the mid-point from 65° to 67.5°C and the final gelatinization temperature from 68° to 70°C. The gelatinization of pearl millet starch occurred at a lower temperature than that of sorghum starch (Table 19). In general it was observed that starches having low solubility and

swelling below 75°C showed greater solubility and swelling at and above 80°C. The peak pasting temperature of the five starches was the same, 76.5°C. Differences in paste viscosity were larger in magnitude after one hour's holding at 95°C and during the cooling cycle. This showed that some starches tended to retrograde more than others.

The peak paste viscosity of pearl millet flour starch was much lower than that of sorghum starch (Badi, Hoseney and Finney, 1976). Pearl millet was shown to have very high amylase activity, about ten times higher than that of wheat grain (Sheorain and Wagle, 1973), and this was probably responsible for the low peak viscosity observed. It is of interest that amylase of pearl millet was observed to be more active against wheat starch than against the starch from pearl millet grain itself (Beleia and Varriano-Marston, 1981a,b). This observation is of great practical importance. Bread prepared from wheat flour blended with 10 percent pearl millet flour had better loaf volume than standard bread prepared from wheat flour containing malt and sugar (Badi, Hoseney and Finney, 1976). Thus pearl millet flour used in partial replacement of wheat flour can be successfully substituted for malt and sugar in the preparation of bakery products such as bread, biscuits and pasta. Subramanian, Jambunathan and Ramaiah (1986) observed that the quality of unleavened bread (*roti*) prepared from pearl millet flours was influenced by swelling capacity, water-soluble flour fraction, water-soluble protein and amylose content of the flour. The swelling capacity of the flour was highly and positively correlated with all the sensory qualities of *roti*, namely colour, texture, odour, taste and acceptability. On the other hand, the amylose content and water-soluble flour fraction were negatively correlated with all these characteristics.

Finger millet

In high-yielding varieties of finger millet analysed by Wankhede, Shehnaj and Raghavendra Rao (1979a), mean starch content was 60.3 (59.5 to 61.25) percent; pentosan 6.6 (6.2 to 7.2) percent; cellulose 1.6 (1.4 to 1.8) percent, lignin 0.28 (0.04 to 0.6) percent; and free sugar 0.65 (0.59 to 0.69) percent. Sucrose (33 percent), glucose and fructose (each 12 percent) and maltose and raffinose (10 percent each) were the major components of the

free sugar of finger millet. The amylose content of the starch in finger millet was 16 percent (Wankhede, Shehnaj and Raghavendra Rao, 1979b), which is lower than the values in normal sorghum and other millets. The swelling capacity and solubility in water at 90°C of the isolated starch of finger millet were lower than for sorghum and similar to those of other millet starches. The high peak viscosity and the increase in viscosity on cooling suggested a strong tendency of the starch to undergo retrogradation. The paste viscosity is reduced and the nutrient density, particularly energy density, is enhanced after malting of the grain, and on this basis weaning food containing 70 parts of malted finger millet and 30 parts of dehulled green gram has been developed (Malleshi and Desikachar, 1982).

Other millets

Foxtail and proso millet have been reported to have both glutenous and non-glutenous endosperm types, while only the non-glutenous type of endosperm is reported to be present in finger and barnyard millets (Tomita *et al.*, 1981). The starch in two foxtail millet varieties was 100 percent amylopectin. Starches of foxtail, proso and barnyard millets were more digestible than maize starch in terms of *in vitro* amylolysis by pancreatic amylase. The glutenous starches were more digestible than non-glutenous types, as in other cereal grains.

The increase in paste viscosity on cooling to 35°C and the further rise after one hour's holding at that temperature indicated the strong tendency of these millet starches to undergo retrogradation. One of the proso varieties, namely Big red proso, was exceptional in that its starch had higher water-binding capacity and gelatinization temperature than that of five other varieties.

PROTEIN CONTENT AND QUALITY

The second major component of sorghum and millet grains is protein. Both genetic and environmental factors affect the protein content of sorghum and millets. In sorghum the variability is large, probably because the crop is grown under diverse agroclimatic conditions which affect the grain composition (Burleson, Cowley and Otey, 1956; Waggle, Deyoe and Smith, 1967; Deosthale, Nagarajan and Visweswar Rao, 1972). Fluctuations in the

protein content of the grain are generally accompanied by changes in the amino acid composition of the protein (Waggle and Deyoe, 1966).

The quality of a protein is primarily a function of its essential amino acid composition. To assess the protein quality, Block and Mitchell (1946) introduced the concept of an amino acid or chemical score, in which the amount of the essential amino acid that is in greatest deficit is expressed as a percentage of the amount present in a standard or reference protein. Egg and human milk proteins, for their very high biological value, have been considered as reference standards. Sorghum and millet proteins differed in their essential amino acid profile (Table 21). However, the most common feature was that lysine was always found to be the most limiting amino acid. The highest deficit of lysine was in the protein of barnyard millet (chemical score 31), closely followed by little millet (chemical score 33). Sorghum protein, with a chemical score of 37, did not differ very much in quality from the proteins of barnyard and little millet.

The primary function of dietary protein is to satisfy the body's needs for nitrogen and essential amino acids. According to the World Health Organization (1985), the chemical score of a protein if calculated in relation to the essential amino acid requirement pattern as reference would be more realistic and indicative of the capacity of the protein to meet human requirements. Such data on chemical score relative to amino acid requirement for different age groups (Table 22) suggested that the inherent capacity of the existing varieties commonly consumed was not adequate to meet the growth requirements of infants and young children, though all of them except sorghum may be able to meet the maintenance requirements in adults.

Grain proteins are broadly classified into four fractions according to their solubility characteristics: albumin (water soluble), globulin (soluble in dilute salt solution), prolamin (soluble in alcohol) and glutelin (extractable in dilute alkali or acid solutions). In solubility fractionation studies with sorghum and pearl, finger and foxtail millets, five protein fractions were obtained (Table 23). The levels of albumin plus globulin were higher in pearl millet varieties than in sorghum, while amounts of the cross-linked prolamin, β -prolamin, were higher in sorghum than in pearl millet.

TABLE 21
Essential amino acid composition (mg/g) and chemical score of sorghum and millet proteins

Grain	Isoleucine	Leucine	Lysine	Methionine	Cysteine	Phenylalanine	Tyrosine	Threonine	Tryptophan	Valine	Chemical score
Sorghum	245	832	126	87	94	306	167	189	63	313	37
Pearl millet	256	598	214	154	148	301	203	241	122	345	63
Finger millet	275	594	181	194	163	325	—	263	191	413	52
Foxtail millet	475	1 044	138	175	—	419	—	194	61	431	41
Common millet	405	762	189	160	—	307	—	147	49	407	56
Little millet	416	679	114	142	—	297	—	212	35	379	33
Barnyard millet	288	725	106	133	175	362	150	231	63	388	31
Kodo millet	188	419	188	94	—	375	213	194	38	238	55

Source: FAO, 1970a; Indira and Naik, 1971.

TABLE 22

Lysine amino acid scores for different age groups based on the 1985 WHO index

Grain	Infant (<1 year)	Preschool child (2-5 years)	Schoolchild (10-12 years)	Adult
Wheat	43	46	62	100+
Rice (husked)	57	61	82	100+
Maize	41	43	58	100+
Sorghum	17-51	18-55	25-74	71-100+
Pearl millet	26-69	28-74	38-100+	100+
Foxtail millet	28-38	30-40	40-55	100+
Finger millet	39-63	41-68	56-91	100+
Kodo millet	46-52	48-55	65-74	100+
Barnyard millet	26	27	37	100+
Proso millet	23-72	24-74	32-98	93-100+

Sources: WHO, 1985; Hulse, Laing and Pearson, 1980.

Apart from a favourable essential amino acid profile, easy digestibility is an important attribute of a good-quality protein. Chemical score does not take into account the digestibility of protein or availability of amino acids. Biological methods based on measurement of growth and nitrogen retention assess the overall nutritional quality of the protein. These methods include determination of protein efficiency ratio (PER), net protein utilization (NPU), biological value (BV) and true protein digestibility (TDP).

Sorghum

Wide variability has been observed in the essential amino acid composition of sorghum protein (Hulse, Laing and Pearson, 1980; Jambunathan, Singh and Subramanian, 1984). Lysine content was reported to vary from 71 to 212 mg per gram of nitrogen and the corresponding chemical score varied from 21 to 62.

Singh and Axtell (1973a) identified two high-lysine Ethiopian sorghum varieties, IS11758 and IS11167. The average lysine content of the whole

TABLE 23
Distribution of protein fractions in sorghum and millet grains (percentage of total protein)

Fraction	Sorghum		Pearl millet		Finger millet		Foxtail millet	
	Range	Mean	Range	Mean	Range	Mean	Range	Mean
Albumin + globulin	17.1-17.8	17.4	22.6-26.6	25.0	17.3-27.6	22.4	11.6-29.6	17.1
Prolamin	5.2-8.4	6.4	22.8-31.7	28.4	24.6-36.2	32.3	47.6-63.4	56.1
Cross-linked prolamin	18.2-19.5	18.8	1.8-3.4	2.7	2.5-3.3	2.78	6.4-17.6	8.9
Glutelin-like	3.4-4.4	4.0	4.7-7.2	5.5	—	—	5.2-11.9	9.2
Glutelin	33.7-38.3	35.7	16.4-19.2	18.4	12.4-28.2	21.2	—	6.7
Residue	10.4-10.7	10.6	3.3-5.1	3.9	16.1-25.3	21.3	—	2.0
Total	91.2-94.0	92.9	78.6-87.5	83.9	74.7-83.9	78.7	—	98.0

Sources: Janakiraman, Singh and Subramanian, 1984 (sorghum and pearl millet); Virupaksha, Ranachandra and Nagaraju, 1975 (finger millet); Monteiro, Virupaksha and Rajagopal Rao, 1982 (foxtail millet).

kernel of IS11758 was 3.13 g per 100 g protein and the total protein content of the kernel was 17.2 percent. IS11167 contained 3.33 g lysine per 100 g protein and 15.7 percent protein. Normal sorghum grown under similar conditions contained 12 percent protein and 2.1 g lysine per 100 g protein. Feeding trials in rats have shown higher PER values for high-lysine varieties (1.78 and 2.05 for IS11758 and IS11167, respectively) than for normal sorghum (PER 0.74 and 1.24).

Another high-lysine mutant, P721, was reported to have 60 percent more lysine than normal sorghum. Van Scyoc, Ejeta and Axtell (1988) have demonstrated that the high lysine of P721 resulted primarily from unusually high amounts of lysine-rich glutelin and low lysine-poor prolamin.

Ejeta and Axtell (1987) observed that in all three of these high-lysine sorghum varieties the lysine content of the germ was normal but the lysine content of the endosperm was higher than in normal sorghum.

Naik (1968), using a modified extraction procedure, observed wide variations in the distribution pattern of protein fractions in the sorghum varieties. Albumin ranged from 2 to 9 percent of total protein, while globulin ranged from 12.9 to 16 percent, prolamin from 27 to 43.1 percent and glutelin from 26.1 to 39.6 percent. Seasonal differences in the distribution pattern of protein fractions were reported (Virupaksha and Sastry, 1968); sorghum varieties grown in the Rabi (dry) season had less prolamin than when grown in other seasons.

Studies on amino acid composition of the protein fractions (Ahuja, Singh and Naik, 1970) showed that the albumin and globulin fractions contained high amounts of lysine and tryptophan and in general were well balanced in their essential amino acid composition. On the other hand, the prolamin fraction was extremely poor in lysine, arginine, histidine and tryptophan and contained high amounts of proline, glutamic acid and leucine. Present in the form of protein bodies, prolamin was found to be a predominant protein fraction directly associated with the protein content of the grain. Glutelin, the second major protein fraction, is a structural component, the protein matrix in the peripheral and inner endosperm of the sorghum kernel.

Both *in vitro* and *in vivo* studies have demonstrated wide variability in protein digestibility of sorghum varieties (Axtell *et al.*, 1981). Values

ranging from 49.5 to 70 percent (Nawar *et al.*, 1970) and from 30 to 70 percent (Silano, 1977) have been reported. Elmalik *et al.* (1986) observed that in rats digestibility of protein of sorghum varieties with intermediate and corneous endosperm texture was 70.3 and 74.5 percent, respectively. These values were lower than that observed for corn protein (78.5 percent). In certain sorghum varieties the presence of condensed polyphenols or tannins in the grains is another factor that adversely affects protein digestibility and amino acid availability (Bach Knudsen *et al.*, 1988; Bach Knudsen, Munck and Eggum, 1988; Whitaker and Tanner, 1989).

In tannin-free sorghum varieties, Sikabbubba (1989) observed that the protein digestibility was inversely correlated with total protein in the grain ($r = -0.548, p < 0.1$), total prolamin ($r = -0.627, p < 0.25$), cross-linked or β -prolamin ($r = -0.647, p < 0.05$) and digestibility of β -prolamin ($r = -0.727, p < 0.01$). In studies in boys aged 10 to 11 years (Kurien *et al.*, 1960), progressive substitution of sorghum for rice in a predominantly vegetarian diet resulted in progressive decrease in protein digestibility from 75 to 55 percent and in apparent nitrogen retention from 4.5 to 2.1 percent. Similar observations were also made in 10- to 11-year-old girls fed sorghum proteins. In nitrogen balance studies conducted with 6- to 30-month-old children recovering from protein energy malnutrition, MacLean *et al.* (1981) observed that for whole-grain gruels prepared from four sorghum

Children fed
sorghum in feeding
trials



varieties including two high-lysine varieties, P721 opaque and IS11758, the average protein digestibility was 46 percent. The protein digestibility of sorghum grain was thus found to be extremely poor as compared to that previously observed for wheat (81 percent), maize (73 percent) and rice (66 percent). However, in a study with decorticated and extruded sorghum product fed to young children (Maclean *et al.*, 1983), the protein digestibility, 81 percent, was much higher than for the whole grain (46 percent). Nitrogen retention, which had been 14 percent in the whole-grain study, was also enhanced, to 21 percent. *In vitro* studies conducted on extruded sorghum (Mertz *et al.*, 1984) also showed that extrusion processing of sorghum grain improved the protein digestibility and hence the nutritive value. Digestibility of sorghum protein was also improved after processing of the grain into *nasha*, a thin fermented porridge used as baby food in the Sudan (Graham *et al.*, 1986). Nitrogen retention was improved in normal Nigerian men fed home-pounded and winnowed sorghum with reduced fibre content (Nicol and Phillips, 1978). These observations emphasize the importance of grain processing to improve the nutritive value of sorghum. A decrease in the protein digestibility of sorghum on cooking was attributed to reduced solubility of prolamin and its reduced digestibility by pepsin (Hamaker *et al.*, 1986).

Pearl millet

Pearl millet, like sorghum, is generally 9 to 13 percent protein, but large variations in protein content, from 6 to 21 percent, have been observed (Serna-Saldivar, McDonough and Rooney, 1991). Lysine is the first limiting amino acid of pearl millet protein. A significant inverse correlation has been reported between the level of protein in the grain and the lysine content of the protein (Deosthale *et al.*, 1971). In high-protein varieties of pearl millet with protein content ranging from 14.4 to 27.1 percent, significant inverse correlations have also been observed between protein and threonine, methionine and tryptophan. The essential amino acid profile shows more lysine, threonine, methionine and cystine in pearl millet protein than in proteins of sorghum and other millets. Its tryptophan content is also higher (Table 21).

Wide variation is observed in the lysine content of pearl millet protein, with values ranging from 1.59 to 3.8 g per 100 g protein. From chemical scores calculated in relation to amino acid requirements for different age groups it was apparent that pearl millet has greater potential to meet the lysine requirements of growing children than most other cereals (Table 22). Pushpamma, Parrish and Deyoe (1972) observed in rat feeding trials a PER of 1.84 for pearl millet as against 1.74 for finger millet, 1.46 for sorghum and 1.36 for maize. This has supported the view that the protein quality of pearl millet ranks quite high in comparison with that of other cereals. On fortification of a pearl millet diet with 0.3 percent lysine hydrochloride, the growth response of rats was enhanced and nearly equalled that of controls fed a casein diet (Howe and Gilfillan, 1970).

Protein quality is associated with the distribution pattern of protein fractions in the grain. Sawhney and Naik (1969) observed large variability in the protein fractions of pearl millet varieties. Albumin ranged from 6.1 to 26.5 percent (mean 15.1 percent), globulin from 3.5 to 14.7 percent (mean 8.7 percent), prolamin from 21.3 to 38.0 percent (mean 30.2 percent) and glutelin from 23.8 to 37.7 percent (mean 30.3 percent). As in other cereals, albumin and globulin are rich in lysine as well as the other basic amino acids arginine and histidine. The globulin fraction appeared to be very rich in sulphur amino acids. The prolamin fraction is characterized by high glutamic acid, proline and leucine and was also shown to be rich in tryptophan, whereas glutelin was found to contain more lysine and less tryptophan.

True protein digestibility in rats fed pearl millet varied little, from 94 to 97 percent (Singh *et al.*, 1987), and it was not affected by the protein content of the grain (Table 24). The digestible energy content was lower in high-protein types because of their high prolamin content. In high-protein genotypes, the lysine content of the protein was low and this was reflected in low biological value and low net protein utilization. But the net utilizable protein (percent protein \times NPU) from the high-protein genotypes was two to three times higher than that from normal millets. Rats fed raw pearl millet flour exhibited higher digestibility of protein and energy than rats fed raw wheat flour (Dassenko, 1980). However, the digestibility and PER were lower when the millet was fed as chapatti, probably because the longer

TABLE 24

Protein quality and digestible energy in dehulled millets (%)

Grain	True digestibility	Biological value	Net protein utilization	Digestible energy
Pearl millet (low protein)	95.9	65.6	62.9	89.9
Pearl millet (high protein)	94.6	58.8	55.7	85.3
Foxtail millet	95.0	48.4	46.3	96.1
Common millet	99.3	52.4	52.0	96.6
Little millet	97.7	53.0	51.8	96.1
Barnyard millet	95.3	54.8	52.2	95.6
Kodo millet	96.6	56.5	54.5	95.7

Sources: Singh *et al.*, 1987 (pearl millet); Geervani and Eggum, 1989 (other millets).

cooking time required for millet chapatti resulted in heat damage to the protein. In nitrogen balance studies in 11- to 12-year-old boys, the apparent protein digestibility of a pearl millet-based diet was 52.9 percent and the nitrogen balance was positive (Kurien, Swaminathan and Subrahmanyam, 1961).

Finger millet

Finger millet is poor in protein content compared with other common cereals (Table 17). Wide variability in the composition of the grain, including its protein content, was reported (Hulse, Laing and Pearson, 1980). Both genetic and environmental factors appear to have an important role in determining the protein content of finger millet (Pore and Magar, 1977; Virupaksha, Ramachandra and Nagaraju, 1975). Prolamin is the major protein fraction in finger millet (Table 23). The high protein of white-grain varieties was attributed to the higher prolamin content of the grain, while the lysine content and hence the protein quality of these varieties are low (Virupaksha, Ramachandra and Nagaraju, 1975). Differences in amino acid composition in different varieties of finger millet are large, and as in other cereals both the lysine content and the methionine content of the protein are inversely correlated with the protein content of the grain. The protein fractions also showed wide variation in their amino acid composi-

tion. While the albumin and globulin fraction was found to contain a good complement of essential amino acids, the prolamin fraction contained higher proportions of glutamic acid, proline, valine, isoleucine, leucine and phenylalanine but low lysine, arginine and glycine. The amino acid composition of prolamin was almost the same as that of endosperm protein.

In vitro studies showed that proteins of finger millet and kodo millet were resistant to pepsin digestion unless the millet was first cooked in an autoclave for 15 minutes or boiled for at least two hours in water. Digestibility of the protein was found to be adversely affected by tannin in the grain, which was as high as 3.42 percent in some of the finger millet varieties studied (Ramachandra, Virupaksha and Shadaksharawamy, 1977). A finger millet diet was found to be adequate to maintain a positive nitrogen balance in adults (Subrahmanyam *et al.*, 1955). The subjects also showed positive calcium and phosphorus balances, and the digestibility of finger millet protein was found to be 50 percent. Supplementation of a finger millet protein diet with lysine or with leaf protein in addition to lysine significantly improved nitrogen retention in young boys. They also showed greater increase in height and weight (Doraiswamy, Singh and Daniel, 1969). The use of finger millet in child and infant feeding, however, appeared to be limited because of its poor digestibility and the large quantity required to meet energy requirements. The growth performance of growing rats fed sprouted finger millet was better than that of animals fed raw grain. However, the protein quality as judged by PER was unaltered by sprouting (Hemanalini *et al.*, 1980). Further processing of germinated finger millet grains by drying, roasting and filtering through a cloth gave a product low in fibre. Animals fed this product as a source of protein showed improved calcium retention, probably because of the low fibre content of the flour.

Malted grains of finger millet have a significantly higher saccharifying enzyme activity useful in brewing. This activity is higher than that of malted sorghum, pearl millet or maize (Rao and Mushonga, 1985). A weaning food with low hot paste viscosity and high energy density was developed in which malted finger millet from which the vegetative portion had been removed was combined with green gram. A mix of 70 parts malted finger millet grains and 30 parts green gram, combined with 10 percent skimmed milk powder,

had a PER of 2.7 and NPU of 63 percent (Malleshi and Desikachar, 1982). An extruded cooked product prepared from a blend of rice (42.5 parts), finger millet (42.5 parts) and defatted soy flour (15 parts) exhibited a significant improvement in protein quality over the unprocessed blend (Dublish, Chauhan and Bains, 1988). The PER values after extrusion had increased from 1.92 to 2.41, while the trypsin inhibitory activity was reduced by about 70 to 100 percent, the tannin content was below measurable amounts and the phytin phosphorus as percentage of total phosphorus had decreased by about 4 to 13 percent. These changes obviously might have contributed to the improved protein quality. A blend of finger millet and defatted soy flour (85:15) on extrusion had a PER of 1.81 before processing and 2.23 after extrusion.

Foxtail millet

The protein in foxtail millet is also deficient in lysine. Its amino acid score (Table 22) is comparable to that of maize (Baghel, Netke and Bajpai, 1985). Monteiro, Virupaksha and Rajagopol Rao (1982) observed large variation in the grain protein content and in the distribution pattern of different solubility fractions. Prolamin constituted the major storage protein (Table 23) and showed a positive correlation with total protein in the grain. Evaluations of the amino acid composition of the protein fractions and of total protein in different varieties have confirmed that lysine is the first limiting amino acid, followed by tryptophan and sulphur amino acids.

With increase in grain protein, the lysine content of the protein decreased. The protein was found to be high in leucine. Naren and Virupaksha (1990) observed that the prolamin was relatively rich in the sulphur amino acid methionine and that the sulphur status of the soil affected the synthesis of prolamin in the grain. In studies on *in vitro* protein digestibility, 90.5 to 96.9 percent of the protein in foxtail millet was digestible by pepsin, and 89.7 to 95.6 percent by papain (Monteiro *et al.*, 1988). Poor digestibility with trypsin (21.6 to 36.9 percent) was improved by prior treatment with acid. The protein quality of dehusked grain (Table 24) was the lowest among the minor millets tested (Geervani and Eggum, 1989). Heat treatment or lysine supplementation improved the protein quality (Geervani and Eggum,

1989). In growing rats fed 10 percent protein, the nitrogen balance improved from 19 to 31 percent when the foxtail millet diet was fortified with lysine; protein digestibility and biological value were also enhanced (Ganapathy, Chitra and Gokhale, 1957). Supplementation of dehusked millet with chickpea raised the PER from 0.5 to 2.2.

Common millet

Though the range of protein content in common millet can be very wide, the values appear to lie most frequently in a narrow range of 11.3 to 12.7 percent, with a mean of 11.6 percent, on a dry-matter basis (Serna-Saldivar, McDonough and Rooney, 1991). The protein of common millet is deficient in lysine as well as threonine, and its tryptophan content is also marginal (Chung and Pomeranz, 1985). Studies on the protein solubility fractions of common millet showed that more than 50 percent of the grain protein was prolamin and the next predominant fraction was glutelin, about 28 percent. The prolamin fraction was very poor in lysine, arginine and glycine compared to the albumin and globulin fraction and had more alanine, methionine and leucine (Jones *et al.*, 1970). When fed as the sole source of protein (8.4 percent) in the diet, common millet had a PER of 0.95. According to data presented by Kuppuswamy, Srinivasan and Subramanian (1958), a common millet diet containing 9 to 11 percent protein had a PER of 1.2 and biological value of 56. A protein isolated (84.8 percent) by alkali extraction of common millet (Tashiro and Maki, 1977) was compared for its protein quality with casein and gluten. In a 21-day feeding trial in young rats with 10 percent protein in the diet, the PER of the protein isolate of common millet was 3.1 while that of casein was 2.8. Animals fed whole millet flour as a source of protein failed to grow. In adult rats the biological value of millet flour was higher than that of the other protein sources. In *in vitro* studies, the isolated protein was digestible by pepsin and by pepsin-pancreatin but not by trypsin.

Other millets

Kodo, barnyard and little millets have been investigated less from the nutritional point of view. Kodo millet grains are enclosed in a hard, corneous

husk which is difficult to remove. The fibre content of the whole grain is very high. Kodo millet has around 11 percent protein, and the nutritional value of the protein has been found to be slightly better than that of foxtail millet but comparable to that of other minor millets (Table 24). Apart from lysine, the protein of kodo millet is deficient in tryptophan (Chung and Pomeranz, 1985). As with other foodgrains, the nutritive value of kodo millet protein was improved by supplementation with legume protein (Rajalakshmi and Mujumdar, 1966). The PER of kodo millet on supplementation with chickpea and amaranth leaves was increased from 0.9 to 1.9 (Patwardhan, 1961b).

Barnyard and little millets are comparable to common millet in their protein and fat content (Geervani and Eggum, 1989), and both are very high in fibre. With lysine amino acid scores of 31 and 33, little millet and barnyard millet have the poorest quality proteins among the millets. Barnyard and little millets are comparable in their protein digestibility, biological value, net protein utilization and digestible energy content (Table 24) and therefore in their overall nutritive value.

LIPID COMPOSITION

Sorghum

The crude fat content of sorghum is 3 percent, which is higher than that of wheat and rice but lower than that of maize. The germ and aleurone layers are the main contributors to the lipid fraction. The germ itself provides about 80 percent of the total fat (Rooney and Serna-Saldivar, 1991). As the kernal fat is mostly located in the germ, in sorghum mutants with a large embryo fraction the fat content is higher (5.8 to 6.6 percent) than normal (Jambunathan, 1980). Variations in reported fat content of the grain can be attributed partly to the different solvent systems used for extraction of kernel fat. Price and Parson (1975) reported that the neutral lipid fraction was 86.2 percent, glycolipid 3.1 percent and phospholipid 10.7 percent in sorghum fat.

No significant difference was reported in fat content among several cultivated and wild sorghum races (Stemler *et al.*, 1976). Fatty acid was significantly higher in kafir, caudatum and wild sorghum than in the bicolor,

durra and guinea groups. On the other hand, caudatum types had the lowest linoleic acid and bicolor, durra and guinea varieties had more than wild and kafir sorghum. Oleic and linoleic acids were negatively correlated with each other. The fatty acid composition of sorghum fat (linoleic acid 49 percent, oleic 31 percent, palmitic 14 percent, linolenic 2.7 percent, stearic 2.1 percent) was similar to that of corn fat but was more unsaturated (Rooney, 1978).

Millets

Finger, foxtail and kodo millets appeared to contain less fat in the kernel than other millets (Table 17), while the fat content of common millet was similar to that of sorghum. The fat content of pearl millet is the highest among the millets.

Lai and Varriano-Marston (1980) observed significant differences in the fatty acid composition of four different bulk populations of pearl millet. Differences in lipid extraction procedures as well as genetic variability were shown to contribute to differences in the fatty acid content of pearl millet (Jellum and Powell, 1971). The principal fatty acids in both free and bound fat were found to be linoleic, oleic and palmitic acids. Distinct differences in fatty acid composition were noted in the neutral lipid, phospholipid and glycolipid fractions (Osagie and Kates, 1984). Neutral lipid was highest in linoleic acid and lowest in palmitic acid; phospholipid was lowest in oleic acid and highest in palmitic acid; and glycolipid was highest in linolenic acid.

The fatty acid composition of common millet and foxtail millet did not differ from that of sorghum (Hulse, Laing and Pearson, 1980). Common millet was found to contain 1.8 to 3.9 percent lipids, and about 24 percent of the grain fat was in the embryo component. The fatty acid profile showed that saturated fatty acids totalled 17.9 to 21.6 percent while unsaturated fatty acids totalled 78 to 82 percent. The unrefined fat extracted from the kernel of common millet contained 8.3 to 10.5 mg vitamin A and 87 to 96 mg vitamin E per 100 g. On refining, all the vitamin A activity was lost and there was significant loss in vitamin E. Vitamin E is also present in the fat extracted from sorghum grain.

MINERALS

The mineral composition of sorghum and millet grains (Table 25) is highly variable. More than genetic factors, the environmental conditions prevailing in the growing region affect the mineral content of these foodgrains.

Sorghum

In the sorghum kernel the mineral matter is unevenly distributed and is more concentrated in the germ and the seed-coat (Hubbard, Hall and Earle, 1950). Pedersen and Eggum (1983) have shown that in milled sorghum flours minerals such as phosphorus, iron, zinc and copper decreased with lower extraction rates. Similarly, pearling the grain to remove the fibrous seed-coat resulted in considerable reduction in the mineral contents of sorghum (Sankara Rao and Deosthale, 1980). However, these studies also showed that the *in vitro* availability of iron as judged by the ionizable iron as percentage of total iron was higher in pearled grain. Dehulling improves iron availability because the hull is rich in phytate, a compound that binds iron and certain other minerals and makes them biologically unavailable (see Chapter 6). Mbosung and Ndjouenkeu (1990) observed that the percentage of soluble and ionizable iron was higher in gruels prepared from mechanically dehulled sorghum than in those prepared from grain milled traditionally using mortar and pestle. The increase in iron availability was attributed partly to the efficient removal of the phytate-rich hull in mechanical milling and partly to the greater destruction of phytate during soaking of the grain prior to dehulling.

In studies in Indian women, absorption of iron was higher from tannin-free than from high-tannin sorghum cultivars (Gillooly *et al.*, 1984). Pearling of the grain improved the absorption of iron from both high- and low-tannin cultivars. Radhakrishnan and Sivaprasad (1980) assessed the bioavailability of iron in normal and anaemic subjects fed diets based on two varieties of sorghum containing 20 and 136 mg of tannin respectively and 160 and 273 mg of phytin phosphorus respectively per 100 g. In normal subjects iron absorption from low- and high-tannin sorghum was essentially similar. However, in anaemic subjects it was significantly lower with high-tannin sorghum. On equalization of the phytate content of the two sorghum

TABLE 25
Mineral composition of sorghum and millets (mg %)^a

Grain	Number of cultivars	P	Mg	Ca	Fe	Zn	Cu	Mn	Mo	Cr
Sorghum	6	352	171	15	4.2	2.5	0.44	1.15	0.06	0.017
Pearl millet	9	379	137	46	8.0	3.1	1.06	1.15	0.07	0.023
Finger millet	6	320	137	398	3.9	2.3	0.47	5.49	0.10	0.028
Foxtail millet	5	422	81	38	5.3	2.9	1.60	0.85	—	0.070
Whole Dehulled	360	68	21	2.8	2.4	1.40	0.60	—	0.030	
Common millet	5	281	117	23	4.0	2.4	5.80	1.20	—	0.040
Whole Dehulled	156	78	8	0.8	1.4	1.60	0.60	—	0.020	
Little millet	5	251	133	12	13.9	3.5	1.60	1.03	—	0.240
Whole Dehulled	220	139	13	9.3	3.7	1.00	0.68	—	0.180	
Barnyard millet	5	340	82	21	9.2	2.6	1.30	1.33	—	0.140
Whole Dehulled	267	39	28	5.0	3.0	0.60	0.96	—	0.090	
Kodo millet	5	215	166	31	3.6	1.5	5.80	2.90	—	0.080
Whole Dehulled	161	82	20	0.5	0.7	1.60	1.10	—	0.020	

^a Expressed on a dry-weight basis.
Sources: Sankara Rao and Devasthale, 1980 (sorghum), 1983 (pearl and finger millets), unpublished (other millets).

meals the difference in iron absorption disappeared. It was concluded that at the levels of tannins present in the two varieties of sorghum, tannins had a minor role in determining the iron bioavailability.

Gillooly *et al.* (1984) found no difference in the iron absorption from porridges prepared from malted and unmalted sorghum. They observed that addition of ascorbic acid facilitated the iron absorption from both porridges, while consumption of tea adversely affected the iron absorption. Iron absorption varied in a narrow range of 72 to 83 percent in rats fed acidic, basic or neutral sorghum *tô*, maize gruel or the fermented sorghum porridge *aceda* (Stuart *et al.*, 1987). However, absorption of zinc was found to be significantly higher, 97 percent, in rats fed fermented sorghum *aceda* than in those fed maize gruel or any of the three types of sorghum *tô* (67 to 78 percent).

Beers brewed with sorghum adjuncts and maize grits are very common in African countries. Derman *et al.* (1980) observed that the iron absorption from beer brewed from sorghum or maize was more than 12 times higher than that from gruel prepared from these two grains. Beer brewed with sorghum adjunct was found to be a concentrated source not only of vitamins such as thiamin and nicotinic acid but also of several minerals including copper, manganese, iron, magnesium, potassium and phosphorus (van Heerden, 1989). With appreciable amounts of protein and starch and no detectable phytate, sorghum beer could make an important contribution to the daily intake of vitamins and minerals in African populations.

Pearl millet

Wide variations have been reported in the mineral and trace-element composition of pearl millet, and as with sorghum the composition and nature of the soil was considered the main environmental factor determining the mineral content of the grain (Hoseney, Andrews and Clark, 1987; Jambunathan and Subramanian, 1988). Milling of pearl millet to a flour with an extraction rate of 75 percent reduced the calcium and iron content by about 66 percent (de Wit and Schweigart, 1970). Dassenko (1980) observed significant losses of calcium, magnesium and sodium but not of iron and potassium on milling pearl millet to a flour with 67 percent extraction rate.

In rat feeding studies, absorption of iron by anaemic animals fed pearl millet as a source of iron (2 mg per kilogram body weight) was 35.7 percent as against 29.7 percent with sorghum, 37.5 percent with maize, 40 percent with soybean and 33.3 percent with bambara nuts (Ifon, 1981). In bioavailability studies with chicks, the magnesium availability was higher from pearl millet than from sorghum (Nwokolo, 1987). However, the millet was found to be poor in available zinc, iron and manganese compared with sorghum.

Malting enhanced severalfold the ionizable iron content of pearl millet and finger millet grains and also significantly increased their soluble zinc content, indicating an improvement in *in vitro* availability of these two elements (Sankara Rao and Deosthale, 1983).

Klopfenstein, Hoseney and Leipold (1985) observed that rats fed pearl millet supplemented with calcium carbonate in the diet continued to grow well after seven weeks of feeding, while those fed unsupplemented millet in the diet ceased to grow after four weeks. It was concluded that calcium was more limiting than lysine or other nutrients in pearl millet when fed to growing rats.

Finger millet

Except for very high calcium and manganese content, the mineral and trace element composition of finger millet is comparable to that of sorghum. Some high-protein (8 to 12.1 percent) and high-yielding varieties of finger millet were also rich in calcium (294 to 390 mg per 100 g) (Babu, Ramana and Radhakrishnan, 1987). Studies conducted in nine- to ten-year-old girls showed that replacement of rice in a rice-based diet with finger millet not only maintained positive nitrogen balance but also improved calcium retention (Joseph *et al.*, 1959). Thus finger millet could be used to overcome the calcium deficiency of a rice diet. *In vitro* studies showed that bioavailability of iron was poor in commonly cultivated and highly pigmented varieties of finger millet grain because of their tannin content. Removal or reduction of tannin either by extraction with solvent or by grain germination enhanced the ionizable iron content. These studies also showed that iron availability in terms of ionizable iron content was higher in white grain, no-tannin finger millet varieties (Udayasekhara Rao and Deosthale, 1988).

Other millets

The total mineral matter as ash content was higher in common, little, foxtail, kodo and barnyard millets than in most commonly consumed cereal grains including sorghum. These minor millets have a highly fibrous hull which is usually removed before consumption. Dehulling was found to result in considerable nutrient losses in all five millets. The extent of these losses was variable and depended upon the mineral content of the species (Sankara Rao and Deosthale, unpublished) (Table 25).

Lorenz (1983) observed that the phytate content of common millet varieties ranged from 170 to 470 mg per 100 g whole grain, and dehulling resulted in a 27 to 53 percent reduction in phytate content. On dehulling, phytin phosphorus decreased 12 percent in common millet, 39 percent in little millet, 25 percent in kodo millet and 23 percent in barnyard millet (Sankara Rao and Deosthale, unpublished).

VITAMINS

Sorghum

Sorghum and millets in general are rich sources of B-complex vitamins. Some yellow-endosperm varieties of sorghum contain β -carotene which can be converted to vitamin A by the human body. Blessin, VanEtten and Wiebe (1958) isolated carotenoids of sorghum and identified lutein, zeaxanthin and β -carotene. Suryanarayana Rao, Rukmini and Mohan (1968) analysed several varieties of sorghum for their β -carotene content. The variations were very large, with values ranging from 0 to 0.097 mg per 100 g of grain sample. In view of the photosensitive nature of carotenes and variability due to environmental factors, yellow-endosperm varieties of sorghum are likely to be of little importance as a dietary source of vitamin A precursor.

Detectable amounts of other fat-soluble vitamins, namely D, E and K, have also been found in sorghum grain. Sorghum as it is generally consumed is not a source of vitamin C. On germination, some amount of vitamin C is synthesized in the grain and on fermentation there is a further rise in the vitamin content (Taur, Pawar and Ingle, 1984). In feeding trials in guinea pigs on diets based on wheat, rice, maize or pearl millet, the vitamin C requirement of the animals for optimal growth was five times higher than

that of animals fed casein in their diets (Klopfenstein, Varriano-Marston and Hoseney, 1981a,b; Klopfenstein, Hoseney and Varriano-Marston, 1981). Guinea pigs on isonitrogenous, isocaloric, nutritionally adequate diets based on sorghum required 40 mg vitamin C per day as against 2 mg on the casein-based diet. Higher levels of dietary ascorbic acid apparently had a niacin-sparing effect on the sorghum-based diet. Interestingly, the animals fed 40 mg ascorbic acid had low levels of cholesterol in their blood and liver. The significance of these observations in relation to the nutrition of predominantly sorghum-eating populations needs further investigation.

Among B-group vitamins, concentrations of thiamin, riboflavin and niacin in sorghum were comparable to those in maize (Table 17). Wide variations have been observed in the values reported, particularly for niacin (Hulse, Laing and Pearson, 1980). The highest niacin content, 9.16 mg per 100 g sorghum, was reported by Tanner, Pfeiffer and Curtis (1947). Ethiopian high-lysine sorghum varieties were also very high in niacin; values per 100 g were 10.5 mg in IS11167 and 11.5 mg in IS11758, as against 2.9 to 4.9 mg in normal sorghum (Pant, 1975).

Niacin in cereal grains exists in a bound form which is alkali soluble but considered biologically unavailable to humans (Goldsmith *et al.*, 1956). Ghosh, Sarkar and Guha (1963) observed that 80 to 90 percent of the niacin in sorghum grains was in bound form and was available for the growth of the microorganism used for niacin assay only after alkali treatment. Adrian, Murias de Queroz and Frangne (1970) followed different extraction procedures and found that in sorghum 20 to 28 percent of the niacin was cold-water extractable and thus biologically available, compared to about 45 percent in maize. Belavady and Gopalan (1966) in their studies in dogs observed that niacin in sorghum grain was completely cold-water soluble and thus available, an observation that was quite different from those of Ghosh, Sarkar and Guha (1963) and Adrian, Murias de Queroz and Frangne (1970). Other studies (Carter and Carpenter, 1981, 1982) showed that niacin in sorghum grain was present as a high-molecular-weight complex and was biologically available to rats after alkali treatment of the grain but not after boiling in water. In boiled grains total niacin per 100 g was 7.07 mg in rice, 5.73 mg in wheat, 4.53 mg in sorghum and 1.88 mg in maize. The proportion

of total niacin available to rats was 41 percent in rice, 31 percent in wheat, 33 percent in sorghum and 37 percent in maize. Thus niacin bioavailability in cereal grains was found to be limited (Wall and Carpenter, 1988).

Other B-complex vitamins present in sorghum in significant amounts are vitamin B₆ (0.5 mg per 100 g), folacin (0.02 mg), pantothenic acid (1.25 mg) and biotin (0.042 mg) (United States National Research Council/National Academy of Sciences, 1982).

Millets

Available data are very meagre regarding the vitamin content of pearl millet, finger millet and minor millets. In thiamin and riboflavin content these millets differed little from sorghum (Table 17). Niacin content, however, was lower in some of them. Ghosh, Sarkar and Guha (1963) found that, as in sorghum, 80 to 90 percent of the niacin in pearl millet grains was biologically unavailable. Adrian, Murias de Queroz and Frangne (1970), however, found that 31 to 40 percent of the niacin in pearl millet was cold-water extractable and thus available. In little millet total niacin was very high (10.88 mg percent), about two to three times higher than in other cereals, but only 13 percent of it was cold-water extractable.

Khalil and Sawaya (1984) found that bread prepared from pearl millet flour by a traditional method was significantly lower in thiamin, pantothenic acid and folic acid than the flour itself. The millet flour was relatively high in pantothenic acid. In nine pearl millet varieties thiamin content varied from 0.29 to 0.4 mg per 100 g, with a mean of 0.34 mg (Chauhan, Suneja and Bhat, 1986). Germination of pearl, finger and foxtail millet grains for 48 hours increased ascorbic acid to 8, 5 and 6 mg per 100 g, respectively. There was also a small but significant increase in thiamin content (Malleshi and Desikachar, 1986a). Opoku, Ohenhen and Ejiofor (1981) observed increases in thiamin, riboflavin, ascorbic acid, vitamin A and tocopherol in pearl millet germinated for 48 hours and kilned at 45°C. Niacin, however, decreased by about 30 percent. Aliya and Geervani (1981) observed increases in thiamin (to 90 percent) and riboflavin (to 85 percent) on fermentation of pearl millet batter. However, steaming the fermented batter decreased the thiamin (to 64 percent) and riboflavin (to 28 percent) below

the initial values of unfermented batter. Similar vitamin losses on fermentation of pearl millet flour were observed by Dassenko (1980). On cooking there was no change in the vitamin content of the fermented product.

DIETARY FIBRE

The term dietary fibre is used to describe a variety of indigestible plant polysaccharides including cellulose, hemicelluloses, pectins, oligosaccharides, gums and various lignified compounds. According to the modified definition of Trowell (1976), dietary fibre is defined as the sum of the lignin and polysaccharides that are not hydrolysed by the endogenous enzymes of the human digestive tract. Kamath and Belavady (1980) found that the major insoluble fibre component of sorghum was cellulose, which varied from 1.19 to 5.23 percent in sorghum varieties. In any seed material there are two sources of dietary fibre, namely the hull or the pericarp and the cell wall structural components. The plant cell walls contain many non-carbohydrate components in addition to lignin, such as protein, lipids and inorganic material, and they modify the properties of the polysaccharides. Several approaches have been suggested for the measurement of total dietary fibre in foods. Each of the methods has certain limitations which may contribute to the observed variations in dietary fibre content reported for various foodstuffs.

Sorghum

Bach Knudsen and Munck (1985) found that a commonly consumed low-tannin Sudanese sorghum variety, Dabar, had total dietary fibre content of 7.6 percent while a high-tannin Sudanese variety, Feterita, contained 9.2 percent. A major proportion of the total dietary fibre in both the varieties was water insoluble (6.5 percent in Dabar and 7.9 percent in Feterita). The acid detergent fibre in the two varieties was also different (2.9 percent in Dabar and 3.6 percent in Feterita). The contribution of polyphenols to the lignin fraction of the dietary fibre was responsible for the higher values of dietary fibre in the high-tannin variety. Cooking of the sorghum as whole-grain porridge decreased the availability of energy, mostly because of the formation of enzyme-resistant starch, therefore apparently increasing the

dietary fibre content of both varieties. Fermentation at pH 3.9 helped overcome the formation of resistant starch and also prevented the formation of lignin during cooking. Compared to wheat, rye, barley or maize, the total dietary fibre in the two sorghum varieties was low. The amount of protein bound to total dietary fibre as well as to acid detergent fibre in the sorghum varieties was much higher than in wheat and other foodgrains, and this binding increased on cooking, especially in the high-tannin sorghum. Fermentation or acidification to pH 3.9 inhibited the protein binding. These observations indicate that the traditional Sudanese fermentation method has important nutritional advantages.

Dietary fibre has certain adverse effects on the availability of some nutrients. The concentration of zinc and iron in the tibia of rats on sorghum diets rich in fibre and phytate was significantly lower than in rats on a non-sorghum diet with low fibre content (Ali and Harland, 1991).

Decortication of the grain is one of the methods to remove fibre. Cornu and Delpeuch (1981) found that the apparent nitrogen digestibility in adult subjects on a diet of 80 percent sorghum decreased from 65.4 to 60.5 percent when the dehusked sorghum in the diet was replaced by whole-grain sorghum. The total faecal matter of subjects on the whole-grain sorghum diet was higher. The nitrogen and formic-acid insoluble material in the faeces also increased.

Karim and Rooney (1972) reported that the pentosan content of sorghum varied from 2.51 to 5.57 percent. Pentosans as they occur in the cell walls of cereal grains are a heterogeneous mixture of polysaccharides, many of which contain proteins.

Earp *et al.* (1983) identified the mixed linked β -glucans in sorghum pericarp, aleurone and endosperm. These β -glucans are water soluble and form viscous, sticky solutions. This property is important in the malting of sorghum and brewing of beer. Klopfenstein and Hoseney (1987) observed that rats fed bread prepared from white flour fortified with β -glucan (7 percent by weight) had serum cholesterol significantly lower than those fed bread from unfortified flour. The cholesterol-lowering property was also shown by the glucans isolated from oat, barley, wheat and sorghum.

Millets

Kamath and Belavady (1980), using the method of Southgate, Hudson and Englyst (1978), found that the total dietary fibre in pearl millet (20.4 percent) and finger millet (18.6 percent) was higher than that in sorghum (14.2 percent), wheat (17.2 percent) and rice (8.3 percent). Singh *et al.* (1987), also using the Southgate method, found that the total dietary fibre content of pearl millet was 17 percent. There are not enough data available on the dietary fibre components of the millets. Bailey, Sumrell and Burton (1979) have isolated pentosan containing a mixture of heterogeneous polysaccharides from the cell wall of pearl millet grains. The pentosan of pearl millet extracted with different solvents including 80 percent ethanol, water and alkali was found to contain seven sugars, the most predominant being arabinose, xylose and galactose, followed by rhamnose and fucose. Emiola and de la Rosa (1981) also studied the water- and alkali-extractable pentosan of pearl millet, but their results were at variance with those of Bailey, Sumrell and Burton (1979), showing an identical pattern for the water- and alkali-soluble pentosan but with ribose rather than fucose as one of the sugars. Emiola and de la Rosa (1981) found that in pearl millet water-soluble non-starch polysaccharides accounted for 0.66 percent of grain weight and water-insoluble non-starch polysaccharides for 3.88 percent. On further purification these values were reduced to 0.42 percent and 0.97 percent, respectively. Wankhede, Shehnaj and Raghavendra Rao (1979a) reported that in finger and foxtail millet the pentosan content was 6.6 and 5.5 percent, respectively. Muralikrishna, Paramahans and Tharanathan (1982) found that the hemicellulose A in little, kodo and barnyard millets was a non-cellulosic β -glucan and the hemicellulose B was composed of hexose, pentose and uranic acid.

Chapter 5

Nutritional quality of foods prepared from sorghum and millets

It stands to reason that when a grain is processed, some nutrients must be removed and also that the removal of any but an exactly proportionate part of any constituent of a seed will affect the nutritional quality of what is left. Consequently, the nutritional effect of milling probably depends as much on the amount of material removed as on the method used to remove it. It is therefore difficult to compare different reports involving different preparative techniques. Reichert and Youngs (1977) reported that traditionally decorticated sorghum and millets contained more oil and ash than abrasively decorticated grains, but the protein content was similar. Pushpamma (1990) reported that decortication reduced total protein and lysine by about 9 and 21 percent respectively, but that it also improved the utilization of the remaining protein. The loss of minerals was minimal. Decortication improved the biological availability of nutrients and consumer acceptability.

Whether the removal of nutrients (and antinutritional factors) is on balance beneficial is a question that must always be analysed carefully. Organoleptic factors must also be considered. What is actually done is not always nutritionally for the best, and what is best in one type of diet is not always what is best for another.

Germination leads to considerable changes in the nutritive quality of a grain. There will obviously be some changes because of the loss of dry matter, but far more important changes, such as increased enzyme activity and the conversion of starch to sugars, result from the growing process. The toxicity of cyanide in germinated sorghum has already been mentioned. The danger of sickness or death from cyanide ingestion must always be borne in mind.

TABLE 26

Effect of time and temperature on nutritional quality of germinated sorghum seeds^a

Time after germination (days)	Germination (%)	Coleoptile length (cm)	RN ^b (%)	PER ^b	Available amino acid (mg/g N)		
					Lysine	Tryptophan	Methionine
0 ^c	—	—	54.6	1.5	13.5	6.8	8.5
25°C							
2	10-15	0.2-0.4	48.6	1.4	24.0	4.8	8.4
3	15-20	0.5-1.0	54.0	1.5	33.0	7.6	11.5
4	25-35	2.5-5.5	67.8	1.8	45.0	15.2	18.6
5	25	2.5-8.5	68.9	1.8	28.0	15.0	15.3
30°C							
2	10	0-1.0	52.4	1.4	15.0	7.2	7.2
3	10-15	2.4-4.5	62.1	1.7	21.0	8.8	7.5
4	20-30	2.5-7.0	58.0	1.6	33.0	12.0	13.8
5	30	3.5-7.5	62.4	1.7	33.0	15.2	14.3
6	30	5.0-10.0	78.3	2.0	69.0	18.6	19.5
35°C							
2	15-20	2.0-3.0	54.7	1.5	30.0	9.4	14.0
3	10	3.5-5.5	62.4	1.7	26.3	8.0	10.2
4	10	4.0-7.0	63.0	1.7	24.0	12.0	10.0

^aN = 1. Seeds were germinated in quart glass jars, dried at 50°C and ground in a Wiley mill.^bPER = 0.286 + 0.022(RNV). Values rounded to nearest 0.1 PER.^cNon-germinated control.

Source: Wang and Fields, 1978.

Wang and Fields (1978) found that germination of sorghum increased the relative nutritive value (RN^b) from 54.6 to 63 percent and the protein efficiency ratio (PER) from 1.5 to 1.7. There were substantial increases in lysine, methionine and tryptophan (Table 26). Malleshi and Desikachar (1986b) reported that germination of finger, pearl and foxtail millets resulted in a slight decrease in total protein and moisture. The main advantage was a reduction in the level of phytate and an increase in the levels

TABLE 27

Means of nutrient contents in sorghum meal^a

Type of meal	Methionine (mg/g N)	Lysine (mg/g N)	Thiamin ($\mu\text{g/g}$)	Riboflavin ($\mu\text{g/g}$)	Niacin ($\mu\text{g/g}$)	RVN (%)
Control	9.1a	11.25a	3.66ab ^{..}	1.34a ^{..}	68.39a ^{..}	45.57 ^{..}
Fermented, 25°C	33.2b	25.68b	3.18a	1.27a	70.88a	55.10a
Fermented, 35°C	34.5b	26.79b	3.87b	1.38a	70.91a	56.17a

^an = 5. Means with different letters are significantly different. ^{..}Significant at P < 0.01; ^{..}Significant at P < 0.05.

Source: Au and Fields, 1981.

of ascorbic acid, lysine and tryptophan. Malleshi, Desikachar and Venkat Rao (1986) also found that germination substantially reduced the amount of phytate, thereby improving the absorption of iron. Sprouting, roasting and sieving reduced the protein content of finger millet from 7.7 to 3.9 percent (Hemanalini *et al.*, 1980).

Changes that take place during fermentation include increases in amino nitrogen, the breakdown of proteins and the destruction of any inhibitors that may be present. Significant increases in various amino acids (particularly methionine) and vitamins have been observed (Kazanas and Fields, 1981; Au and Fields, 1981) as a result of fermentation of sorghum (Table 27); an increase in the nutritive value was also reported. Axtell *et al.* (1981) found that fermented products of sorghum were more digestible than unfermented products. Fermentation or acidification inhibited the protein-binding effect of polyphenols (Bach Knudsen and Munck, 1985). Obizoba and Atii (1991) reported that fermentation reduced the level of cyanide in sprouted sorghum. It also reduced enzyme-resistant starch and decreased the concentration of the flatulence-causing sugars raffinose and stachyose (Odunfa and Adeyele, 1987). The starch and protein digestibility of *rabadi*, a product made from pearl millet, increased with longer fermentation (Dhankher and Chauhan, 1987).

MacLean *et al.* (1983) showed that decortication and extrusion can markedly improve the apparent digestibility of sorghum protein fed to young children. The addition of calcium hydroxide before extrusion also improved digestibility (Fapojuwo, Maga and Jansen, 1987).

CULINARY PREPARATIONS

Foods from sorghum and millets can be grouped in two categories, traditional products and non-traditional industrial products. Unprocessed or processed grain can be cooked whole or decorticated and if necessary ground to flour by any of the traditional or industrial methods described in Chapter 3. A detailed classification of traditional foods from sorghum and millets has been developed (Vogel and Graham, 1979; Rooney, Kirleis and Murty, 1986). They can be classified broadly into breads, porridges, steamed products, boiled products, beverages and snack foods (Rooney, Kirleis and Murty, 1986; Rooney and McDonough, 1987). The various uses of sorghum and millets in India are shown in Table 28 (Pushpamma and Chittemma Rao, 1981). Foods from pearl millet in different parts of the world are given in Table 29; the products are similar to those from sorghum. The following are a few of the many different ways sorghum and millet can be prepared for eating. (Spices and condiments may be added to suit individual tastes.)

Whole grains

Immature sorghum grains are sometimes roasted whole. Sorghum and to a lesser extent pearl millet and finger millet are popped (dry heated to make the grain explode) in villages in India (Subramanian and Jambunathan, 1980). The grains are usually popped on special hot plates or on sand baths

Traditional foods
prepared from
sorghum in India



TABLE 28

Forms of utilization of sorghum and millets in India

Food	Product type	Form of grain used	Consumers	
			No.	Percentage ^a
Sorghum				
<i>Roti</i>	Unleavened flat bread	Flour	1 132	67
<i>Sangati</i>	Stiff porridge	Mixture of coarse particles and flour	811	48
<i>Annam</i>	Rice-like	Dehulled grain	586	35
<i>Kudumulu</i>	Steamed	Flour	295	18
<i>Dosa</i>	Pancake	Flour	213	13
<i>Ambali</i>	Thin porridge	Flour	167	10
<i>Boorelu</i>	Deep fried	Flour	164	10
<i>Pelapindi</i>	Popped whole grain and flour	Mixture of coarse particles and flour	94	6
<i>Karappoosa</i>	Deep fried	Flour	42	3
<i>Thapala chakkalu</i>	Shallow fried	Flour	24	1
Pearl millet				
<i>Roti</i>	Unleavened bread	Flour	706	88
<i>Sangati</i>	Stiff porridge	Mixture of coarse particles and flour	305	38
<i>Annam</i>	Rice-like	Dehulled grain	268	33
<i>Kudumulu</i>	Steamed	Flour	229	29
<i>Boorelu</i>	Deep fried	Flour	145	18
<i>Dosa</i>	Pancake	Flour	26	3
<i>Thapala chakkalu</i>	Shallow fried	Flour	24	3
<i>Ambali</i>	Thin porridge	Flour	22	3
Finger millet				
<i>Sangati</i>	Stiff porridge	Rice broken and flour	308	63
<i>Roti</i>	Unleavened bread	Flour	151	31
<i>Ambali</i>	Thin porridge	Flour	149	31

TABLE 28 (*continued*)

Food	Product type	Form of grain used	Consumers	
			No.	Percentage ^a
Proso millet				
Annam	Rice-like	Dehulled grain	236	94
Muruku	Deep fried	Flour	96	38
Karappoosa	Deep fried	Flour	37	15
Ariselu	Deep fried	Flour	17	7
Foxtail millet				
Annam	Rice-like	Dehulled grain	517	96
Ariselu	Deep fried	Flour	21	4
Sangati	Stiff porridge	Flour	12	2
Roti	Unleavened bread	Flour	7	1
Kodo millet				
Annam	Rice-like	Dehulled grain	76	96

^aOf surveyed consumers of each grain, percentage who consume the specified preparation. For example, 67 percent of sorghum consumers reported that they consume sorghum prepared as *roti*.

Source: Pushpamima and Chittemma Rao, 1981.

heated over a fire. Popped sorghum is said to be more tender than popped corn, contains less hull, does not clog spaces between the teeth and makes less noise when eaten. In general, the desired characteristics of sorghum for popping are small grain size, a medium to thick pericarp, hard endosperm and a very low germ-to-endosperm ratio (Murty *et al.*, 1982). Significant genotypic differences exist in sorghum for popping volume, expansion ratio and popping percentage (Thorat *et al.*, 1988). In finger millet, wide varietal variations exist for popping quality. White-seeded types are preferred; brown-seeded varieties were found to be not particularly suitable for popping (Malleshi and Desikachar, 1981; Shukla *et al.*, 1986).

Grits

Decorticated millet grains are sometimes boiled in water and served like rice. Grits made from sorghum and pearl millet are also cooked like rice in

TABLE 29
Traditional foods made with pearl millet

Type of food	Common names	Countries
Unfermented bread	<i>Roti, rotii</i>	India
Fermented bread	<i>Kisra, dosa, dosai, gallettes, injera</i>	Africa, India
Thick porridge	<i>Ugali, tuwo, saino, dalaki, aceda, atap, bogobe, ting, tutu, kalo, karo, kwon, nshimba, nuchu, tō, tuo, zaafi, asidah, mato, sadza, sangati</i>	Africa, India
Thin porridge	<i>Uji, ambali, edi, eko, kamo, nasha, bwa kal, obushera</i> <i>Ogi, oko, akamu, kafa, koko, akasa</i>	Africa, India Nigeria, Ghana
Steamed cooked products	<i>Couscous, degue</i>	West Africa
Boiled, rice-like foods	<i>Annam, acha</i>	Africa, India
Snack foods		Africa, Asia
Sweet/sour opaque beers	<i>Burukutu, dolo, pito, talla</i>	West Africa
Sour opaque beers	<i>Marisa, busaa, merissa, uwaga, mwenge, munkoyo, utshwala, utywala, ikigage</i>	Sudan, southern Africa
Non-alcoholic beverages	<i>Mehewu, amahewu, marewa, magou, leting, abrey, huswa</i>	Africa

Source: Rooney and McDonough, 1987.

many countries. Sorghum boiled like rice is called *kichuri* in Bangladesh, *lehtawagen* in Botswana, *kaoliang mifan* in China, *nifro* in Ethiopia and *oka baba* in Nigeria (Subramanian *et al.*, 1982). Dehulled sorghum and pearl millet grains are also cooked like rice in India. A sorghum product similar to rice called *sori* has been developed in Mali. In China, grain with 80 percent extraction rate is used for boiled sorghum. Sometimes pearled sorghum, rice and beans are mixed and cooked. In some countries sorghum varieties with hard, small grains are specially grown for processing into food which can be used as a substitute for rice.

Flaking is a process that is widely used for making foods from cereals, and both sorghum and millet can be flaked. Decorticated grits are moistened with water and steamed or cooked to gelatinize some of the starch, dried to a moisture content of about 17 percent and then either pounded in a special mortar (Desikachar, 1975) or rolled between flaking rolls (Rizley and Suter, 1977) to produce a flat product. The flakes are further dried and can be stored

for several months. Sorghum has been flaked in the United States to improve its digestibility for beef cattle. In India *poha* and *avilakki* are flaked foods based on sorghum and millet.

In many West African countries, sorghum and pearl millet grits are steamed to produce a coarse and uniformly gelatinized product called *couscous*. Sorghum with a pigmented testa produces reddish-brown *couscous* with an astringent taste. *Couscous* can be consumed fresh or can be dried; in its dried form it can be stored for more than six months (Galiba *et al.*, 1987). The dried product can be reconstituted in water, milk or sauce. It is used as a convenience food in the Sahel.

Porridge

Porridges are the major foods in several African countries. They are either thick or thin in consistency. These porridges carry different local names. Thick porridges are called *ugali* (Kenya, United Republic of Tanzania, Uganda), *tô* (Burkina Faso, the Niger), *tuwo* (Nigeria), *aceda* (the Sudan), *bogobe*, *jwa ting* (Botswana) and *sadza* (Zimbabwe). The nutritional value of whole and decorticated sorghum grains and dishes made from them is shown in Table 30. The biological value of sorghum *ugali* was superior to that of the raw grain, but the true digestibility of protein decreased when sorghum was processed into *ugali* (Table 31). In Mali, parts of Senegal and Guinea, *tô* is alkali treated and has a pH of 8.2. In Burkina Faso, it is acid treated to a pH of about 4.6. In other regions of Africa, the *tô* is neutral. These treatments have implications in the taste preferences and nutrition of the people.

Thin porridges are called *uji* (Kenya, United Republic of Tanzania), *ogi* or *koko* (Nigeria, Ghana), *edi* (Uganda), *rouye* (the Niger, Senegal), *nasha* (the Sudan), *rabri* (India), *bota* or *mahewu* (Zimbabwe) and *motogo we ting* (Botswana). Sorghum flour, sorghum malt, pigeon pea and groundnut are mixed in different proportions to improve the nutritional value of traditional porridges (Nout *et al.*, 1988).

In Uganda, a sour porridge called *bushera* is prepared by boiling ungerminated millet flour to produce a thick paste. Flour made from freshly germinated millet is then mixed into it. This sweetens the porridge and also

TABLE 30

Chemical composition of whole and decorticated sorghum grains and dishes^a

Variety and preparation	Protein (N × 6.25)	Ash (% w/w)	Fat (% w/w)	Crude fibre (% w/w)	Starch + sugar (% w/w)
Tetron, whole grain	10.9	1.78	5.1	2.1	72.5
Dabar, whole grain	11.6	1.68	4.0	2.0	73.4
Feterita, whole grain	13.4	2.07	4.1	2.1	71.0
Dabar, decorticated (79% extraction)	11.3	1.39	3.3	1.0	79.4
Feterita, decorticated (80% extraction)	14.9	0.87	2.7	0.8	74.3
Dabar, <i>ugali</i> , whole grain	11.3	1.56	4.1	2.2	69.9
Dabar, <i>ugali</i> (acid), whole grain	12.7	1.62	3.8	2.2	69.7
Feterita, <i>ugali</i> , whole grain	14.1	1.39	4.0	2.2	66.5
Tetron, <i>kisra</i> , whole grain	11.3	1.80	5.3	2.1	71.2
Feterita, <i>kisra</i> , whole grain	14.1	1.59	5.1	2.4	68.8
Dabar, <i>kisra</i> , decorticated (79% extraction)	12.6	1.23	4.2	1.1	74.8

^a All data are expressed on a dry-matter basis.Source: Eggum *et al.*, 1983.

lowers its viscosity. *Bushera* can be kept for three to four days before it starts to ferment. Ultimately it will become a strongly alcoholic drink.

Fermented porridge is made in several regions in Africa. Changes occur during fermentation that are the result of the activity of microorganisms – bacteria, yeasts and moulds. Fermentation processes have evolved largely as a result of practical needs. The palatability and the texture of foods can be changed and their shelf-life can often be improved by fermenting them. In eastern Africa, a suspension of maize, millet, sorghum or cassava flour in water is fermented before or after cooking to make a thin porridge. Oniang’O and Alnwick (1988) described fermented porridge made in Africa from sorghum, finger millet and pearl millet. Fermented porridges are variously thought to promote lactation and to be unsuitable for young children. The shelf-life of fermented porridge is quite short, usually less than

TABLE 31
Protein quality of whole and decorticated sorghum grains and dishes

Variety and preparation	Amino acid (g/16 g N)				True protein digestibility (%)	Biological value (%)	Net protein utilization (%)	Utilizable protein (%)
	Lysine	Threonine	Methionine + cysteine	Proline				
Tetron, whole grain	2.3	3.3	3.8	8.0	21.2	94.5	57.0	53.8
Dabar, whole grain	2.1	3.1	3.6	8.2	22.1	95.4	54.9	52.4
Feterita, whole grain	1.9	3.1	3.5	8.2	22.7	95.8	48.6	46.6
Dabar, decorticated (79% extraction)	1.9	3.1	3.5	8.3	22.4	100.0	53.5	53.5
Feterita, decorticated (80% extraction)	1.6	3.0	3.5	8.6	23.5	99.6	43.9	43.7
Dabar, ugali, whole grain	2.1	3.0	3.5	7.9	21.6	87.5	60.8	53.2
Dabar, ugali (acid), whole grain	2.1	3.0	3.4	7.8	21.3	94.4	54.5	51.4
Feterita, ugali, whole grain	1.9	3.2	3.5	7.9	22.4	82.4	58.3	48.0
Tetron, kisra, whole grain	2.3	3.2	3.6	8.1	22.2	92.8	52.7	48.9
Feterita, kisra, whole grain	2.3	3.1	3.5	8.5	24.0	93.2	50.8	47.3
Dabar, kisra, decorticated (79% extraction)	2.3	3.0	3.7	8.9	25.3	96.9	55.3	53.4
LSD _{0.05}						1.2	1.2	1.3

Source: Eggen et al., 1983.

30 hours. In the Sudan, a thin fermented porridge called *nasha* is prepared with sorghum. Tomkins, Alnwick and Haggerty (1988) identified some of the bacteria and moulds they found in *nasha* and also described a fermented porridge called *ting* from Botswana. *Ogi*, a popular fermented porridge in Nigeria, is prepared using sorghum, millet and maize in various proportions (Steinkraus, 1983; Tomkins, Alnwick and Haggerty, 1988). The predominant volatile and non-volatile acids in *ogi* are lactic and acetic acids, respectively. Traces of formic acid have also been detected. These give *ogi* its characteristic aroma and its sour taste. Light-coloured *ogi* with mild sourness is preferred. However, in Kenya, brown *oji* is preferred. Maize *ogi* contains more energy (calories) than sorghum *ogi* (Table 32). However, the protein, fat and minerals on a dry-weight basis are higher in sorghum *ogi* than in maize *ogi* (Brown *et al.*, 1988).

The *chibuku* beer consumed in southern Africa is basically a thin fermented porridge, usually made from sorghum.

Breads and other baked products

Flat breads are made by baking batters made with flour and water on a hot pan or griddle. Almost any flour may be used. The batter can be based on sorghum, millet or any other cereal and it may or may not be fermented. These flat breads are known by many local names: *roti* and *chapatti* in India, *tuwo* in parts of Nigeria, tortillas in Central America, etc.

Unfermented breads include *roti* and tortillas. *Roti* and *chapatti* made from sorghum or millets are common foods in India, Bangladesh, Pakistan and Arab countries. More than 70 percent of sorghum grown in India is used for making *roti* (Murty and Subramanian, 1982).

Tortillas, which are prepared in Mexico and Central America, are similar to *roti* except that the grain is lime-cooked and wet milled. Although corn is the preferred grain for making tortillas, sorghum is widely used and is well accepted in Honduras (Dewalt and Thompson, 1983). Sometimes tortillas are made by mixing sorghum and corn. White sorghum is the preferred sorghum for making tortillas. Sorghum can be dehulled to reduce the off-white colour of the product. Tortillas prepared from blends of yellow maize and pearly sorghum (15 percent) had lighter colour than 100 percent yellow

TABLE 32
Proximate composition of maize and sorghum ogi obtained from study villages^a

Type of ogi	Moisture (g)	Protein (g)	Fat (g)	Crude fibre (g)	Carbohydrate (g)	Ash (g)	Energy (kcal)	Protein energy (%)
Per 100 g wet weight								
Maize	54.0 ± 1.9	3.5 ± 0.2	2.2 ± 0.2	0.2 ± 0.1	39.8 ± 2.1	0.3 ± 0.1	193.0 ± 7.4	7.2 ± 0.5
Sorghum	68.2 ± 4.6	4.4 ± 0.1	1.7 ± 0.1	0.9 ± 0.2	24.2 ± 4.2	0.7 ± 0.1	129.5 ± 18.5	13.8 ± 1.9
Per 100 g dry weight								
Maize	7.6 ± 0.5	4.8 ± 0.5	0.4 ± 0.1	86.5 ± 1.0	0.6 ± 0.3	420.0 ± 2.7		
Sorghum	14.0 ± 1.9	5.4 ± 0.4	2.9 ± 0.2	75.6 ± 2.1	2.1 ± 0.1	406.9 ± 0.1		

^aMean ± SD.

Source: Brown *et al.*, 1988.

maize tortillas and were found acceptable (Choto, Morrad and Rooney, 1985). Sorghum cultivars Dorado, Sureno and Tortillero from Central America and two hybrids from the Texas Agricultural Experiment station gave tortillas with the best colour and texture (Almeida-Dominguez, Serna-Saldivar and Rooney, 1991). Sorghum kernels with thick white pericarp and yellow endosperm from plants with tan colour and straw-coloured glumes have excellent potential for the manufacture of tortillas.

Injera (Ethiopia) and *kisra* (the Sudan) are the major fermented breads made from sorghum flour (Gebrekidan and Gebre Hiwot, 1982). Teff is the preferred cereal for *injera* preparation. However, sorghum and teff can be mixed, and sorghum alone is also often used. The quality of *injera* is determined in part by the extent of fermentation. In general, children are given lightly fermented *injera* with mild sourness. *Kisra* is a traditional and staple food of the Sudan, prepared from sorghum and millet (Badi, Bureng and Monawar, 1987). It is made with a fermentation starter which shortens the time required for fermentation to less than 16 hours (Badi, Bureng and Monawar, 1988).

A comparison of sorghum and millet flours and bread (*roti*) made from them (Tables 33 to 35) indicated that baking did not affect the chemical composition including the fatty acids (Khalil *et al.*, 1984; Sawaya, Khalil and Safi, 1984). A slight increase in tyrosine, lysine and methionine content was observed when sorghum flour was made into fermented bread. Baking at 300°C for 15 minutes decreased arginine, cystine and lysine content in pearl millet bread.

Eggum *et al.* (1983) compared the nutritional quality of sorghum grain and *kisra* made from it. Sorghum is deficient in lysine and therefore has a low biological value. On the other hand, the true digestibility of protein, as well as digestible energy, is very high, with values above 90 percent. Variety was observed to have only a minor influence on the nutritional quality of *kisra* when preparations from several sorghum varieties were compared (Tables 30 and 31).

Many studies have been done to explore the potential for making loaf bread with composite flours that include either sorghum or millet, and there are no technical difficulties in using any of these flours. Casey and Lorenz

TABLE 33

Proximate composition and tannin content of sorghum flour and bread^a

Product	Moisture (%)	Crude protein ($N \times 6.25$)	Crude fat (%)	Crude fibre (%)	Ash (%)	Carbohydrate (by difference) (%)	Tannins ^b (%)
Flour							
White sorghum	12.4	15.3	4.7	2.3	2.2	75.5	0.09
Reddish-white sorghum	12.1	15.9	5.1	2.5	2.3	74.2	0.27
Bread							
White sorghum	27.2	15.7	4.0	2.5	2.5	75.3	0
Reddish-white sorghum	32.2	16.2	5.1	2.4	2.4	73.9	0
Reddish-white sorghum, fermented	35.4	16.4	4.9	2.9	2.2	73.6	0

^a Means of duplicate determinations (variation < 5%) expressed on dry-weight basis, except moisture which was determined in fresh samples.

^b Expressed as catechin equivalents (CE).

Source: Khalil *et al.*, 1984.

TABLE 34

Mineral composition of sorghum flour and bread (mg %)^a

Product	Na	K	Ca	P	Mg	Fe	Zn	Cu	Mn
Flour									
White sorghum	21	458	18	396	54	5.0	3.3	0.8	3.5
Reddish-white sorghum	23	463	16	407	58	4.5	3.2	0.7	3.4
Bread									
White sorghum	133	308	30	259	49	5.4	2.4	0.6	2.6
Reddish-white sorghum	160	308	23	256	54	5.0	2.3	0.6	2.3
Reddish-white sorghum, fermented	174	300	27	187	57	4.2	2.5	0.7	2.8

^a Means of duplicate determinations (variation < 5%) expressed on dry-weight basis.

Source: Khalil *et al.*, 1984.

TABLE 35
Proximate composition and tannin content of pearl millet flour and bread^a

Product	Moisture (%)	Crude protein (N × 6.25)	Crude fat (%)	Crude fibre (%)	Ash (%)	Carbohydrate (by difference) (%)	Energy (kcal/100 g)	Tannins (%)
Flour								
As-is basis	9.7 ± 0.8	15.7 ± 0.3	5.7 ± 0.2	2.5 ± 0.7	2.0 ± 0.1	64.4 ± 2.1	372 ± 10.5	0.17 ± 0.05
Dry basis		17.4	6.3	2.8	2.2	71.3	412	0.19
Bread								
As-is basis	26.6 ± 1.5	12.7 ± 0.4	4.1 ± 0.2	2.1 ± 0.3	1.9 ± 0.2	52.6 ± 1.8	299 ± 9.2	0
Dry basis		17.3	5.6	2.8	2.6	71.9	407	0

^a Means ± standard deviation ($n > 3$).
Source: Sawaya, Khalil and Safi, 1984.

(1977) reported that a bread made with part millet flour had excellent texture and a flavour similar to that of whole wheat bread. There is always a steady deterioration of bread quality as the percentage of non-wheat flour is increased. If the flour is coloured (as is the case with pearl millet and abrasively decorticated sorghum that contains too many brown sorghum seeds), it is usually the extent of discoloration that limits the amount of non-wheat flour that can be used. In most other cases the limiting factor is the density of the loaf. Unless other additives (usually expensive imports) are used, about 10 percent of non-wheat flour is the limit most people will accept, although many reports have claimed that breads made using much higher rates of addition were acceptable. Cakes and biscuits can be made using flour with much higher levels of non-wheat flour, but again, as with bread, the quality of the product deteriorates as the substitution level increases. Composite flour has been used commercially in bread in several countries, but it is usually accepted only when there is a shortage of wheat flour, and even then unwillingly.

Pasta and noodles

Pasta products (noodles) such as spaghetti and macaroni are usually made from semolina or from flour of durum wheat or common wheat or a mixture of both. Wheat has a unique property of forming an extensible, elastic and cohesive mass when mixed with water. Sorghum and millet flours lack these properties when used alone.

Sorghum is inferior to wheat for making pasta, both because it contains no gluten and because its gelatinization temperature is higher than that of wheat. Miche *et al.* (1977) made pasta from mixtures of sorghum with wheat. They found that to obtain products of good cooking quality it was necessary to add some gelatinized starch to the sorghum flour before extrusion. The pasta quality is influenced by the quality of both the sorghum flour and the starch. White sorghum is preferable for pasta products as its colour is similar to that of wheat flour. A composite flour consisting of 70 percent wheat and 30 percent sorghum produced acceptable pasta.

Noodles made with 20 percent proso millet flour were acceptable (Lorenz and Dilsaver, 1980). The reduction of flour mass during cooking (cooking

loss) at this level of addition was similar to that of wheat noodles used as a control. Cooking loss increased with 40 or 60 percent millet flour.

Faure (1992) made pasta from mixtures of sorghum, millet and wheat. He found that the quality of the pasta was strongly related to the characteristics of the flour that was used and particularly to the way the flour was dried. There should be less than 1 percent ash and 1 percent fat in any material that is used. Proper hydration is necessary. Regrinding and intensive shearing during mixing and extrusion improves hydration. It is difficult to hydrate large pieces of corneous endosperm.

Desikachar (1977) prepared noodles by extruding boiled sorghum dough through a press and then steaming and drying it. In China, sorghum noodles are made using a special device.

Weaning foods

Germinated sorghum flour, called "power flour" (*kimea* in the United Republic of Tanzania), reduces the viscosity of the food product. It is thus possible to use double the quantity of flour to make a product of similar consistency, so the energy density of weaning foods can be increased (Seenappa, 1988). Sorghum and millets are used in weaning foods in countries such as Ethiopia, India, the United Republic of Tanzania and Uganda. Seenappa (1988) described sorghum and millet weaning foods that are being promoted in a number of African countries.

Use of sorghum- and millet-based weaning foods prepared using extrusion and malting techniques has been found successful. These foods have been promoted as high-energy or high-protein foods but would have better acceptance and be more popular if the cost could be reduced.

The quality of weaning foods prepared from cowpea and malted or roller-dried sorghum was evaluated (Malleshi, Daodu and Chandrasekhar, 1989). The weaning food formulation based on malted sorghum and malted cowpea was nutritionally superior to roller-dried weaning food prepared using the unmalted raw materials. The available lysine content was 3.85 percent in the malted food and 2.95 percent in roller-dried sorghum food. The protein efficiency ratio of malted food was 2.26, significantly higher than that of the roller-dried food (1.87). The cooked paste viscosity

of malted sorghum was considerably lower than that of the roller-dried sorghum.

Traditional beverages

Though beverages are not major foods, they serve as a source of energy in several countries. Thin fermented porridges are commonly prepared and used as a drink in African countries. They are considered foods and provide important nutrients. Traditional beer, *amgha*, and a wine, *affouk*, prepared from sorghum in Cameroon were found to be nutritionally superior to sorghum flour (Chevassus-Agnes, Favier and Joseph, 1976) as they provide additional riboflavin, thiamine and lysine. Derman *et al.* (1980) found that iron absorption from maize and sorghum beer was more than 12 times higher than that from the constituents that were used to prepare the beer. In traditional sorghum beer, most of the thiamine and about half of the riboflavin and niacin are associated with beer solids which contain the yeast (van Heerden and Glennie, 1987). The beer with the highest total solids contained the highest amounts of minerals and trace elements (van Heerden, Taylor and Glennie, 1987). Thus the beer is a source of vitamins, iron, manganese, magnesium, phosphorus and calcium. The beer contained 26.7 g starch and 5.9 g protein per litre.

Lager beer can also be produced from sorghum. In Nigeria, sorghum has been tested as a barley malt substitute for producing beer (Obilana, 1985). Beer has been produced successfully by blending equal amounts of sorghum and barley. Lager beer was brewed from sorghum malt using the three-stage decoction method and 30 percent sucrose as an adjunct (Okafor and Aniche, 1987). In Rwanda, a new type of beer is produced using local sorghum and barley (Iyakaremye and Twagirumukiza, 1978). Up to 40 percent sorghum mixed with barley malt makes acceptable beer.

Amylopectin starches are not suitable for lager as they cause difficulty in filtration. Varieties with low starch gelatinization temperature may be suitable. Good malting barley or cereal usually has white floury or starchy endosperm. Similarly, sorghum with predominantly floury endosperm is preferred for malting. Sorghum and corn grits are similar in amino acids, proteins and starch composition (Canales and Sierra, 1976), and sorghum

may confer additional oxidative stability because of its fatty acid composition.

Distilled alcohol can also be produced with suitable modifications and sorghum may have good potential in the industry. Distilled spirits are produced from sorghum in China, where the alcoholic beverage industry is a major consumer of sorghum grain.

Traditional opaque beer, for which sorghum and millets are valuable raw materials, is a popular beverage in several countries in Africa. It is called *chibuku* in Zimbabwe, *impeke* in Burundi, *dolo* in Mali and Burkina Faso and *pito* in Nigeria. The main attributes of this product are short shelf-life of about one week, low alcohol content, acidic nature, suspended solids and a characteristic taste and colour (Chitsika and Mudimbu, 1992). Opaque beer is more a food than a beverage. It contains high proportions of starch and sugars, besides proteins, fat, vitamins and minerals. In its manufacture white sorghum with less polyphenols is preferred, although red and brown sorghum varieties are also used. Red sorghum imparts a pinkish-brown colour to the beer. High-tannin sorghum is not desirable for beer production. The malt used for the manufacture of beer should have high diastatic activity and solubility. Malts are also sources of lactobacilli and essential nutrients.

Extruded products

Extrusion is being used increasingly often for the manufacture of snack foods. In extrusion processes, cereals are cooked at high temperature for a short time. Starch is gelatinized and protein is denatured, which improves their digestibility. Antinutritional factors that are present may be inactivated. Microorganisms are largely destroyed and the product's shelf-life is thereby extended. The products are easily fortified with additives.

So far, sorghum and millet extrusion products have not yet been produced on a commercial scale. Fapojuwo, Maga and Jansen (1987) used two low-tannin sorghum varieties in extrusion studies. Extrusion improved the digestibility of one variety from 45.9 to 74.6 percent and of the other from 43.9 to 68.2 percent. The cooking temperature was the variable that most influenced digestibility. Youssef *et al.* (1990) used two varieties of sorghum (one brown, one white) to make 16 different extrusion products. The

proportion of sorghum in the formulations ranged from 45 to 97 percent. These studies showed that sorghum can be used with other cereals to make acceptable extruded products.

IMPROVING NUTRITIONAL QUALITY

No one legume or cereal can provide adequate amounts of all nutrients to meet the nutritional requirements of a child. However, even before knowledge on protein content, protein quality, digestibility and the nutrient requirements of humans became available, it was recognized that mixing legumes with cereals in the diet could improve overall nutrition. The present and newly derived knowledge in these areas makes it possible to blend, mix or fortify one food material with others so that the resulting fortified mix has not only better nutritional quality but also the necessary attributes for consumer acceptance.

The nutritional quality of sorghum and millets, especially the former, is poor. Therefore attempts have been made to fortify these cereals with legumes or other cereals to make nutritionally superior and acceptable products. Cost, availability of ingredients and marketability must be taken into consideration if fortification is to be implemented successfully on a sustained basis.

Sorghum and pearl millet have been successfully used in feeding programmes after fortification with legumes. Vimala, Kaur and Hymavati (1990) described various infant mixes based on sorghum and pearl millet and fortified with soybean, green gram, red gram or Bengal gram flour (Table 36). They were evaluated through rat feeding trials and nitrogen balance studies in children.

It is possible to fortify malted finger millet (*ragi*) weaning food with green gram. The food has the advantage of having low cooked paste viscosity and has high energy density when mixed in the proportion of 70 percent malted *ragi* flour and 30 percent green gram flour. The NPU of this food was observed to be 52 percent and was comparable to that of a commercially available weaning food (Malleshi, Desikachar and Venkat Rao, 1986).

Okeiyi and Futrell (1983) evaluated the protein quality of various combinations of sorghum with cereals and legumes. These included (dehulled)

TABLE 36

**Formulations tested and developed for adoption in feeding programme
(millet and pulse mixes)**

Ingredients	Proportion
Sorghum <i>rawa</i> (semolina) : soybean flour : skim milk powder	70:25:5
Sorghum <i>rawa</i> : soybean flour : sugar	70:10:20
Sorghum flour : pigeon pea flour	80:20
Pearl millet flour : green gram flour	70:30
Pearl millet flour : black gram flour	70:30
Pearl millet flour : Bengal gram flour	70:30

Source: Vimala, Kaur and Hymavati, 1990.

sorghum, wheat and soy flours; sorghum, wheat, cowpea and soy flours; sorghum, wheat and cowpea flours plus peanut butter; sorghum and wheat flours plus peanut butter; and sorghum, wheat and soy flours plus peanut butter. A diet of sorghum, wheat and soy flours met the FAO recommendations for required amino acids. Over 25 percent of the energy of this diet was provided by fat and 10 percent of the energy was provided by protein as recommended by the United Nations Protein Advisory Group for the formulation of high-protein foods for children. The diet had the same high PER as casein.

Brookwalter, Warner and Anderson (1977) evaluated the stability of sorghum fortified with soy and cottonseed flour in different proportions. The various formulations were stored at -18°C (control), 49°C for two months, 37°C for six months and 25°C for 12 months. All combinations displayed adequate stability as measured by change in available lysine, fat, acidity and flavour. The flavour of all blends was acceptable.

In Burundi, sorghum fortified with maize and soy flours, locally known as *musalac*, has been used as a baby and adult food. It has the following composition: 35 percent sorghum flour, 30 percent maize flour, 20 percent soybean flour, 10 percent sugar and 5 percent milk powder. This combination has about 16 percent protein, with 3.76 percent of protein contributed by lysine, and 440 kcal per 100 g of product. *Musalac* is very popular;

TABLE 37

Mean protein intake and net available protein in children on different diets

Diet	Protein intake		Net available protein		FAO reference protein requirements ^a
	(g)	(g/kg)	(g)	(g/kg)	
Finger millet	29.7	1.31	13.5	0.60	0.72
Finger millet + L-lysine	29.9	1.32	15.8	0.70	0.72
Finger millet + L-lysine + DL-threonine	30.4	1.35	18.0	0.80	0.72
Skim milk powder	28.3	1.25	21.2	0.94	0.72

^a From FAO, 1965.Source: Daniel *et al.*, 1965.

60 t/month were sold commercially in 1989, and production is expected to reach 9 000 tonnes by the year 2000.

The quality of a *ragi* diet was evaluated by feeding it to eight 11- to 12-year-old girls in Mysore, India (Daniel *et al.*, 1965). In addition to *ragi*, the diet included peanut oil, red gram dhal, condiments and skim milk powder. After the diet was followed for four days as acclimatization period, material was collected for analysis during the next four days. The retention of nitrogen on the finger millet diet was very low (6.1 percent of intake) and the biological value (BV) and net protein utilization (NPU) were 67.0 and 45.5 percent respectively (Table 37). Supplementation of the finger millet diet with L-lysine caused a significant improvement in nitrogen retention (13.6 percent of intake), BV (75.9 percent) and NPU (52.7 percent). When the *ragi* diet was supplemented with both L-lysine and DL-threonine, highly significant improvements in the nitrogen retention (21.3 percent of intake), BV (81.2 percent) and NPU (59.3 percent) were observed. The corresponding values obtained for skim milk powder were 33.2, 85.3 and 74.8 percent, respectively. Net available protein showed good improvement on supplementation with lysine and threonine.

Supplementing various types of millets with chickpea has shown good improvement in the protein efficiency ratio as shown in Table 38 (Casey and Lorenz, 1977).

TABLE 38

PER of diets based on millets or blends of millet and chickpea^a

Protein source	PER
Foxtail millet	0.80
Proso millet	1.10
Proso millet + chickpea	1.80
Pearl millet	1.60
Pearl millet + chickpea	2.16
Finger millet	2.00
Finger millet + chickpea	2.10
Rice	2.09
Whole wheat	1.30

^aProtein content in diet: 10 percent. As a supplemental protein source, chickpea provided 40 percent of protein.
Source: Casey and Lorenz, 1977.

Composite flours

Composite flour technology initially referred to the process of mixing wheat flour with cereal and legume flours for making bread and biscuits. However, the term can also be used in regard to mixing of non-wheat flours, roots and tubers, legumes or other raw materials (Dendy, 1992). One example is the mixture of sorghum and maize flour for tortillas.

Diluting wheat flour with locally available cereals and root crops was found to be desirable to encourage the agricultural sector and reduce wheat imports in many developing countries. In Africa there has been an ever-increasing demand for wheat products such as bread. Africa is not a major wheat-growing region, but it produces large quantities of other cereals such as sorghum and millets. It has been reported that replacing wheat with 20 percent non-wheat flour for the manufacture of bakery products would result in an estimated savings in foreign currency of US\$320 million annually (FAO, 1982). At 30 percent substitution the savings would be US\$480 million annually. Thus composite flour technology holds excellent promise for developing countries. Although actual consumer trials have been rare, products made with composite flour have been well accepted in

Colombia, Kenya, Nigeria, Senegal, Sri Lanka and the Sudan (Dendy, 1992).

When sorghum or millets are used for bread-making, addition of bread improvers or modification of the bread-making process is needed. A higher level of substitution is possible with hard than with soft wheat flour (United Nations Economic Commission for Africa, 1985). For the production of biscuits from composite flours, the fat content of the non-wheat flour should be kept as low as possible to promote a longer shelf-life.

Crabtree and Dendy (1979) reported that bread could be produced from composite flour made by co-milling wheat with pearl, proso, barnyard or finger millets. The proportion of millet in the flour can be up to 15 percent. Potassium bromate treatment of the dough tends to improve the loaf volume. Bread containing 10 percent pearl millet flour had an excellent texture and flavour similar to that of whole-wheat bread (Badi, Hoseney and Finney, 1976; see also Perten, 1972).

Sorghum flour milled at 80 percent extraction rate could be blended with white wheat flour for bread-making without any adverse effect (Rao and Shurpalekar, 1976). Acceptability studies conducted at the Food Research Centre in Khartoum, the Sudan, indicated that breads made with composite flour of 70 percent wheat and 30 percent sorghum were acceptable. Milling at 72 to 75 percent extraction rate yielded fine sorghum flour that is more suitable for bread-making. Consumer acceptance trials in Nigeria indicated that breads made with 30 percent sorghum flour were comparable to 100 percent wheat bread (Aluko and Olugbemi, 1989; Olatunji, Adesina and Koleoso, 1989). The protein content of composite flour was lower than that of wheat flour, while its crude fibre was higher. Addition of pentosan improved the quality of bread made with composite flour. The Institute of Food Technology in Dakar, Senegal, prepared a bread consisting of 30 percent millet and 70 percent wheat using the popular millet varieties Souna and Sanio (Thiam, 1981). Another bread, called *pamble*, was prepared with 15 percent millet and 85 percent wheat. Bread with 30 percent sorghum and 70 percent wheat was also prepared in Senegal (Thiam and Ndoye, 1977). Breads with up to 15 percent proso millet were acceptable and comparable to white wheat bread (Lorenz and Dilsaver, 1980).

A combination of 80 percent non-wheat cereal and 20 percent wheat can be used to produce biscuits with acceptable quality. Sorghum and pearl millet flour blended with wheat flour can be used to make biscuits (Badi and Hoseney, 1976, 1977). Olatunji, Adesina and Koleoso (1989) reported that a proportion of 55 percent sorghum could be used for biscuits without adversely affecting biscuit quality. Proso millet was found suitable for making biscuits; biscuit spread and quality score increased with increased levels of proso millet flour because of its high fat content (Lorenz and Dilsaver, 1980). Millet flour imparted a slight grittiness, however. Pearl millet could replace 50 percent of the wheat for cake and 80 percent for biscuits (Thiam, 1981). In Senegal, traditional foods such as *laax*, *conus conus* and *beignets* (fritters) are prepared by mixing millet flour with rice, maize or wheat flour (Thiam, 1981).

ALTERNATIVE USES OF SORGHUM AND MILLET

Sorghum and pearl millet production has considerably increased in several countries during the past few years. With the simultaneous increase in the production of wheat and rice and the available surplus in storage, millets face competition from the utilization point of view. There is already an increasing trend of using wheat or rice in place of sorghum even in those regions where sorghum has been the traditional staple grain in the past.

Sorghum and millets will continue to be major food crops in several countries, especially in Africa (and in particular in Nigeria and the Sudan, which together account for about 63 percent of Africa's sorghum production). These grains will be used for traditional as well as novel foods. However, there is a need to look into the possibilities of alternative uses. Though sorghum and millets have good potential for industrial uses, they have to compete with wheat, rice and maize. Sorghum in particular could be in great demand in the future if the technology for specific industrial end uses is developed. Although pearl millet has some potential for industrial use, other millets have limited potential because of their small grain size and the associated difficulties of adopting a suitable dehulling technology. However, they can be considered for animal and poultry feed. There is a need to compare their performance as feed in comparison with maize.

Sorghum and millets can be adopted for other food products by using appropriate processing methods. Dehulling and milling practices to improve the quality of foods made from sorghum and millets have been described in Chapter 3. It may be possible to select grain types with improved milling quality that will make these crops competitive with other cereals in terms of utilization. Wheat milling technology with suitable modification can be effectively used for grinding sorghum and millets. Although bread can be produced from whole sorghum flour, the quality of the bread can be improved by using sorghum flour from which the bran fraction has been removed by passage through sieves (Caser *et al.*, 1977). Kulkarni, Parlikar and Bhagwat (1987) reported that sorghum malt could be used to make biscuits, weaning foods and beer wort. Addition of up to 40 percent sorghum malt in biscuits caused reduction in stack height and increase in spread because of increased water absorption.

The use of sorghum in common foods such as *idli* (a steamed product), *dosa* (a leavened product) and *ponganum* (a shallow-fat-fried product) can be popularized for wider use in sorghum-growing areas (Subramanian and Jambunathan, 1980). A few important sun-dried or extruded and sun-dried products from sorghum are *papad*, *badi* and *kurdigai*. These products usually have a shelf-life of over one year. They can be popularized through marketing channels similar to those used for rice products. A wide range of bakery and snack products prepared with dehulled sorghum were accepted by consumers in Andhra Pradesh, India (Andhra Pradesh Agricultural University, 1991). It was indicated that these foods should be marketed commercially to make them reach more people and become more popular.

Chapter 6

Nutritional inhibitors and toxic factors

As with other foodstuffs, certain nutritional inhibitors and toxic substances are associated with sorghum and millet grains. Antinutritional factors can be classified broadly as those naturally present in the grains and those due to contamination which may be of fungal origin or may be related to soil and other environmental influences. These factors modify the nutritional value of the individual grains, and some of them have very serious consequences. The following is a brief account of some of the antinutrients and toxic substances associated with sorghum and millets.

PHYTATE

Phytate represents a complex class of naturally occurring phosphorus compounds that can significantly influence the functional and nutritional properties of foods. Although the presence of these compounds has been known for over a century, their biological role is not completely understood. Phytic acid, myo-inositol 1,2,3,4,5,6-hexakis(dihydrogen phosphate), is the main phosphorus store in mature seeds. Phytic acid has a strong binding capacity, readily forming complexes with multivalent cations and proteins. Most of the phytate-metal complexes are insoluble at physiological pH. Hence phytate binding renders several minerals biologically unavailable to animals and humans.

Doherty, Faubion and Rooney (1982) analysed several varieties of sorghum and found that in the whole grain phytin phosphorus ranged from 170 to 380 mg per 100 g; over 85 percent of the total phosphorus in the whole grain was bound as phytin phosphorus. Wang, Mitchell and Barham (1959) studied the distribution of phytin phosphorus in sorghum grain and found

that a greater percentage of phytic acid was in the germ than in the bran and the least was in the endosperm. Dehulling can remove 40 to 50 percent of both phytate and total phosphorus. It was observed that phytin phosphorus constituted 82 to 91 percent of total phosphorus in the whole grain, 56 to 84 percent in the dehulled grain and 85 to 95 percent in the bran. In the fractions obtained through traditional milling, phytin phosphorus content was greatest in the bran, less in the whole grain and lowest in the dehulled grain. This suggested that the bran and aleurone layers of the grain are a major reservoir of phytate and total phosphorus in sorghum. As milling of soft-endosperm varieties removes only a small amount of pericarp, milling causes less decrease in phytin phosphorus in these varieties. Bioavailability of iron in sorghum for human subjects was found to be affected more by phytin phosphorus than by tannin content of the grains (Radhakrishnan and Sivaprasad, 1980). On pearling of sorghum grain, a significant increase in ionizable iron and soluble zinc content indicated improved bioavailability of these two micronutrients, which was attributed partially to the removal of phytate, fibre and tannin along with the bran portion during pearling (Sankara Rao and Deosthale, 1980).

In pearl millet, values reported for phytin phosphorus varied from 172 mg per 100 g (Sankara Rao and Deosthale, 1983) to 327 ± 32 mg per 100 g (Chauhan, Suneja and Bhat, 1986). The values reported by Simwemba *et al.* (1984) were within this range. Ionizable iron was inversely correlated and soluble zinc negatively correlated with phytin phosphorus. Sankara Rao and Deosthale (1983) further observed that malting of the grain significantly reduced the phytin phosphorus content of both pearl and finger millets. This decrease was accompanied by significant increases in ionizable iron and soluble zinc, indicating improved bioavailability of these two elements. Germination of finger millet varieties progressively decreased phytin phosphorus content of the grain (Udayasekhara Rao and Deosthale, 1988). After 48-hour germination with removal of the vegetative portion, the total phosphorus in malted grains decreased by 16, 12 and 9 percent in pearl, finger and foxtail millet, respectively (Malleshi and Desikachar, 1986b). Phytin phosphorus decreased significantly from 38 to 20 percent on germination of pearl millet. However, in finger and foxtail millets the decrease in

phytin phosphorus was very small. A weaning food based on germinated wheat, pearl millet, chickpea, mung bean and sesame contained only 4.39 mg phytin phosphorus per 100 g, as against 10 mg per 100 g in the mix prepared from ungerminated grain (Nattress *et al.*, 1987). In a fermented Indian preparation of pearl millet known as *rabadi*, the phytin phosphorus after nine-hour fermentation had decreased by 27 to 30 percent (Dhankher and Chauhan, 1987).

POLYPHENOLS

Widely distributed polyphenols in plants are not directly involved in any metabolic process and are therefore considered secondary metabolites. Some polyphenolic compounds have a role as defence chemicals, protecting the plant from predatory attacks of herbivores, pathogenic fungi and parasitic weeds. Polyphenols in the grains also prevent grain losses from premature germination and damage due to mould (Harris and Burns, 1970, 1973). Dreyer, Reese and Jones (1981) observed that polyphenols protect seedlings from insect attack.

Phenolic compounds in sorghum can be classified as phenolic acids, flavonoids and condensed polymeric phenols known as tannins. Phenolic acids, free or bound as esters, are concentrated in the outer layers of the grain. They inhibit growth of microorganisms and probably impart resistance against grain mould.

Flavonoids in sorghum, derivatives of the monomeric polyphenol flavan-4-ol, are called anthocyanidins. The two flavonoids identified to be abundant in sorghum grains are luteoforol (Bate-Smith, 1969) and apiforol (Watterson and Butler, 1983). The latter compound was also found in sorghum leaves. Jambunathan *et al.* (1986) observed that resistance to grain mould rather than to birds (Subramanian *et al.*, 1983) was associated with flavan-4-ol content of the grain. Though low-molecular-weight flavonoids from other plant sources were found to be antinutritional in rats (Mehansho, Butler and Carlson, 1987), so far there has been no evidence that sorghum flavonoids have similar properties.

Tannins are polymers resulting from condensation of flavan-3-ols. Gupta and Haslam (1980) referred to sorghum tannins as procyanidins because

they thought that cyanidin was usually the sole anthocyanidin involved. During grain development, flavonoid monomers are synthesized and then condense to form oligomeric proanthocyanidins of four to six units.

Some varieties of sorghum containing high tannin in the grain were found to be bird resistant (Burns, 1971; Tipton *et al.*, 1970). Tannins are the most abundant phenolic compound in brown bird-resistant sorghum. During maturation the brown-sorghum grain develops astringence which imparts resistance against bird and grain mould attack. This quality is important in arid and semi-arid regions where other crops fail. In some of these regions, annual losses in grain production as high as 75 percent or sometimes more have been reported (McMillan *et al.*, 1972; Tipton *et al.*, 1970).

Tannins, while conferring the agronomic advantage of bird resistance, adversely affect the grain's nutritional quality (Salunkhe *et al.*, 1982; Salunkhe, Chavan and Kadam, 1990; Butler *et al.*, 1984, 1986). Growth retardation was observed in chicks fed high-tannin sorghums. Tannins in the grain impart an astringent taste which affects palatability, reducing food intake and consequently body growth (Butler *et al.*, 1984). Tannins bind to both exogenous and endogenous proteins including enzymes of the digestive tract, affecting the utilization of proteins (Asquith and Butler 1986; Griffiths, 1985; Eggum and Christensen, 1975). Several studies in rats, chicks and livestock have shown that high tannin in the diet adversely affects digestibility of protein and carbohydrates and reduces growth, feeding efficiency, metabolizable energy and bioavailability of amino acids (Rostango, 1972). Some of the antinutritional effects of high-tannin sorghum may be due to associated low-molecular-weight flavonoids which are readily absorbed, inhibiting the metabolic utilization of digested and absorbed foodstuffs (Butler, 1988; Mehansho, Butler and Carlson, 1987).

There is no direct evidence regarding antinutritional effects of dietary tannins in human subjects, although high dietary tannin may have some carcinogenic effect (Morton, 1970; Singleton and Kratzer, 1973). Iron absorption in Indian women was lower when they were fed porridge prepared from bird-resistant high-tannin sorghum in place of porridge prepared from tannin-negative sorghum (Gillooly *et al.*, 1984). On the other hand, studies in normal and anaemic subjects (Radhakrishnan and

Sivaprasad, 1980) have shown that availability of iron was affected more by phytic acid than by the tannin content of the grain. The tannin content of the so-called high-tannin sorghum used by these workers was only 160 mg catechin equivalents per 100 g, and this was much lower than that normally found in bird-resistant sorghum varieties.

Considerable efforts have been made to develop methods to improve the nutritional quality of bird-resistant sorghum (Salunkhe, Chavan and Kadam, 1990). Tannins and associated polyphenols are concentrated in the testa or seed-coat and can be removed by milling. However, milling by traditional (mortar and pestle) as well as mechanical methods was shown to result in considerable losses in nutrients, and the flour produced was poor in yield as well as in nutritional quality (Chibber, Mertz and Axtell, 1978). Mwasaru, Reichert and Mukuru (1988) have suggested that for milling to be commercially economical, varieties of sorghum with round grains and hard endosperm and containing just adequate tannin for bird resistance and other agronomically desirable properties should be developed. They have identified such varieties giving flour extraction levels of 70 percent or higher on abrasive dehulling (Reichert, Mwasaru and Mukuru, 1988).

Price, Hagerman and Butler (1980) observed that the tannin content of sorghum flour decreased when it was mixed into batter, and there was further reduction on cooking. However, the growth of rats fed cooked or uncooked batter was lower than that of animals fed raw flour. Germination was also found to decrease tannin content in sorghum (Osuntogun *et al.*, 1989) and finger millet (Udayasekhara Rao and Deosthale, 1988). However, the tannin content of the germinated sorghum rose again significantly upon drying.

Different methods have been tried to inactivate or detoxify the tannins in bird-resistant sorghums to improve their nutritional quality (Salunkhe, Chavan and Kadam, 1990). Moisturizing the grains with alkali several hours prior to utilization, including treatment of whole grain with dilute aqueous ammonia, was found to be quite effective (Price and Butler, 1979). In traditional processing of high-tannin sorghums, prior treatment of the grain with alkalis is an important step. In making sorghum beer, the grains are soaked overnight with moistened wood ash; the alkalis released from the ash were found to inactivate the tannins (Butler, 1988). This observation is very

important, since the product before fermentation is used for feeding children in certain parts of eastern Africa. Muindi and Thomke (1981) found that treatment of high-tannin sorghum with *Magadi* soda solution was also effective in detoxification of tannins. Other methods suggested to improve the nutritional quality of bird-resistant sorghum include treatment with formaldehyde (Daiber and Taylor, 1982) and polyethylene glycol (Hewitt and Ford, 1982), gelatin (Butler *et al.*, 1986) and high-moisture reconstitution (Teeter *et al.*, 1986). Supplementation of high-tannin diets with orthophosphoric acid or dicalcium phosphate (Ibrahim *et al.*, 1988) or sodium bicarbonate (Banda-Nyirenda and Vohra, 1990) also had a positive effect in terms of detoxification of tannins.

Among millets, finger millet was reported to contain high amounts of tannins (Ramachandra, Virupaksha and Shadaksharawamy, 1977), ranging from 0.04 to 3.47 percent (catachin equivalents). *In vitro* protein digestibility was negatively associated with the tannin content of finger millet varieties. In studies reported by Udayasekhara Rao and Deosthale (1988), white varieties of finger millet had no detectable tannin, while the tannin content of brown varieties ranged from 351 to 2 392 mg per 100 g. After extraction of tannin the ionizable iron in brown finger millet varieties rose by 85 percent, and addition of the extracted tannin to white varieties reduced the ionizable iron by 52 to 65 percent. These studies indicated that the poor iron availability (represented by low ionizable iron) in brown varieties is due to their high tannin content.

In the fermented pearl millet product *rabadi*, polyphenols decreased by 10 to 12 percent after nine hours of fermentation (Dhankher and Chauhan, 1987).

DIGESTIVE ENZYME INHIBITORS

Inhibitors of amylases and proteases have been identified in sorghum and some millets (Pattabiraman, 1985). Chandrasekher, Raju and Pattabiraman (1981) screened millet varieties for inhibitory activity against human salivary amylase. Japanese barnyard, common, kodo and little millet strains had no detectable activity. One pearl millet and two sorghum strains did not show any inhibitory activity against α -amylase, while other strains of

sorghum and pearl, foxtail and finger millets showed appreciable activity, indicating it to be a varietal and species character. Sorghum had the highest inhibitory activity against human, bovine and porcine amylases; foxtail millet did not inhibit human pancreatic amylase, while extracts from pearl and finger millets inhibited all α -amylases tested. The inhibitors were non-dialysable and were inactivated by pepsin treatment. Inhibitors from sorghum and foxtail millets were more thermolabile than those from finger and pearl millets.

Similar screening for protease inhibitors (Chandrasekher, Raju and Pattabiraman, 1982) showed that kodo, common and little millet varieties had no protease-inhibitory properties while pearl, foxtail and barnyard millets displayed only antitrypsin activity. Finger millet extracts were found to have the highest activity against bovine trypsin (33.3 units) and chymotrypsin (12.5 units), as well as against porcine elastase (Pattabiraman, 1985). Extracts from sorghum and pearl, foxtail and barnyard millets inhibited the proteolytic enzymes of both human and bovine pancreatic preparations.

Manjunath, Veerbhadrappa and Virupaksha (1981) purified and characterized trypsin inhibitors from finger millet and found the final preparation homogeneous by sodium dodecyl sulphate polyacrylamide gel electrophoresis (SDS-PAGE) at pH 4.3 and ultracentrifugation. The purified anti-trypsin inhibitor was found to be stable over a wide range of temperature and pH (3 to 12). While it was active against bovine trypsin, it did not inhibit bovine α -chymotrypsin, pepsin, papain or subtilisin. It was found to have inhibitory properties against salivary and pancreatic amylases. Almost simultaneously, Shivaraj and Pattabiraman (1981) independently reported that a single bifunctional protein factor in finger millet had inhibitory activity against trypsin and amylase with two separate active sites.

Chandrasekher and Pattabiraman (1982) purified and characterized two trypsin inhibitors from pearl millet. Both were active against bovine trypsin but inactive against bovine α -chymotrypsin. Fairly stable to heat, the two inhibitors were also stable under a wide pH range, from 1 to 9.

The nutritional significance of the enzyme inhibitors present in sorghum and millets is not clearly understood; more research on enzyme inhibitors of cereal grains is needed.

GOITROGENS

Iodine is an essential micronutrient for all animal species, and iodine deficiency is among the most widely prevalent nutritional problems in many developing countries (DeMaeyer, Lowenstein and Thilly, 1979). Though environmental iodine deficiency is a prerequisite to goitre formation, the incidence of goitre in animals and humans with normal dietary intake of iodine suggests there are other factors in the aetiology of simple goitre. The observation that cabbage feeding produced thyroid hyperplasia in rabbits was the first milestone of progress in this field. A large number of foodstuffs possess antithyroid agents, collectively designated as goitrogens. The isolation and identification of *l*-5-vinyl-2-thioxazolidone, a goitrogen of some foods in the Cruciferae family (Astwood, Greer and Ettlinger, 1949), led to the search for similar agents in more commonly eaten foodstuffs. Cyanogenic glycoside, which can be hydrolysed to highly potent antithyroid thiocyanates, was found to be present in cassava tubers, a staple of tropical Africa, and was implicated in the high incidence of goitre in cassava-eating populations.

Another staple food implicated in the aetiology of goitre is pearl millet. In the Sudan, Osman and Fatah (1981) observed that in rural Darfur Province, where pearl millet was the only staple, the incidence of goitre was higher than in urban regions where other foodgrains such as sorghum were consumed. Consumption of pearl millet is considered one of the factors responsible for the high incidence of goitre in rural populations. A positive correlation observed between the incidence of goitre and per caput production of pearl millet in six African countries (Klopfenstein, Hoseney and Leipold, 1983a) supports this viewpoint. Furthermore, Osman and Fatah (1981) observed that rats fed pearl millet diets developed abnormal thyroid-hormone patterns with hyperplasia while animals fed sorghum were unaffected. A thioamide-type goitrogen was suspected to be present in the pearl millet grown and consumed in the region. Sudanese girls with goitre had relatively high serum isothiocyanate which was attributed to their consumption of pearl millet (Osman, Basu and Dickerson, 1983).

Feeding trials in rats showed that the goitrogen inhibited deiodination of thyroxine (T4) to triiodothyronine (T3), the metabolically more active form

of the hormone. Iodine supplementation did not alleviate the goitrogenic effect of pearl millet.

Studies reported by Klopfenstein, Hoseney and Leipold (1983b) showed that the goitrogenic principle in pearl millet was present in both the bran and endosperm portions of the grain and was not destroyed by grain fermentation. The observation that autoclaving of the millet reduced its goitrogenic properties suggested a volatile or heat-labile nature of the active principle. Birzer, Klopfenstein and Leipold (1987) found that the goitrogenic principle of pearl millet was alcohol extractable and probably present as the *c*-glucosyl flavones vitexin, glucosyl vitexin and glucosyl orientin. The alcohol extract of wetted and dried pearl millet grain was found to be more goitrogenic; it contained no vitexin nor its glycosides but showed the presence of the phenolic compounds phloroglucinol, resorcinol and *p*-hydroxybenzoic acid, which are known for their antithyroid properties. Antithyroid activity was reported to be higher in extracts prepared from boiled or stored pearl millet (Gaitan *et al.*, 1989).

Tempering the grain to 26 percent moisture overnight prior to milling resulted in a flour with no goitrogenic activity (Klopfenstein, Leipold and Cecil, 1991). A strong positive correlation was observed between *c*-glycosyl flavone level and the thyroid histopathology and hormone pattern. Yellow-coloured pearl millet was less goitrogenic than brown or grey millet. More evidence is needed, however, to understand the mechanism of the antithyroid action of the flavonoids in pearl millet (Birzer and Klopfenstein, 1988).

AMINO ACID IMBALANCE AND PELLAGRA

Dietary deficiency of niacin, a B-complex vitamin, is well accepted as a causative factor of the nutritional disorder known as pellagra in humans. The classical clinical manifestations of pellagra are bilateral and symmetrical photosensitive dermatitis, diarrhoea and dementia or impairment of the mental function. Endemic pellagra in sorghum-eating populations was first described by Gopalan and Srikantia (1960), particularly in poor agricultural labourers around Hyderabad in Andhra Pradesh. About 1 percent of the hospital admissions were pellagrins and about 10 percent of the mental-

hospital cases showed clinical features of the disease (Gopalan and Vijayaraghavan, 1969).

Traditionally, pellagra has been associated with consumption of maize. It is rarely observed in populations subsisting on other cereals or millets. The pellagragenic properties of maize are largely explained by the poor niacin bio-availability and low tryptophan content of its protein. On the other hand, niacin in sorghum is biologically available (Belavady and Gopalan, 1966) and the tryptophan content of sorghum protein is not low. These observations suggest that the aetiology of pellagra in sorghum eaters might be different. A common feature of sorghum and maize is that the proteins of both these grains contain a relatively high proportion of leucine. It was therefore suggested that an amino acid imbalance from excess leucine might be a factor in the development of pellagra.

Clinical, biochemical and pathological observations in experiments conducted in humans as well as laboratory animals have shown that high leucine in the diet impairs the metabolism of tryptophan and niacin and is responsible for the niacin deficiency in sorghum eaters (Belavady, Srikantia and Gopalan, 1963; Srikantia *et al.*, 1968; Ghafoorunissa and Narasinga Rao, 1973). High leucine is also a factor contributing to the pellagragenic properties of maize, as shown by studies in which dogs fed the low-leucine maize variety Opaque-2 did not suffer from niacin deficiency while those fed high-leucine Deccan hybrid maize showed typical features of the canine form of pellagra (Belavady and Gopalan, 1969). All these observations support the hypothesis that excess leucine in sorghum is aetiologically related to pellagra in sorghum-eating populations.

Further studies have shown that the biochemical and clinical manifestations of dietary excess of leucine could be counteracted not only by increasing the intake of niacin or tryptophan but also by supplementation with isoleucine (Belavady and Udayasekhara Rao, 1979; Krishnaswamy and Gopalan, 1971). These studies suggested that the leucine/isoleucine balance is more important than dietary excess of leucine alone in regulating the metabolism of tryptophan and niacin and hence the disease process.

Pellagra is not endemic in all the areas where sorghum is the main staple. This probably suggests that factors other than excess leucine and poor

leucine/isoleucine balance in sorghum proteins are responsible for the development of the disease. Recent investigations have shown that vitamin B₆ is involved in the metabolism of leucine as well as that of tryptophan and niacin, and it is therefore suggested that regional differences in the prevalence of pellagra might be related to the nutritional status of the population in terms of vitamin B₆ (Krishnaswamy *et al.*, 1976).

Hulse, Laing and Pearson (1980), after reviewing the literature available to them, expressed the view that experimental evidence is lacking from other laboratories to support the hypothesis regarding the excess leucine in sorghum as an aetiological factor leading to niacin deficiency. Studies in human subjects (Nakagawa *et al.*, 1975) as well as in rats (Nakagawa and Sasaki, 1977) did not show any effect of excess dietary leucine on tryptophan and niacin metabolism. Similarly, Cook and Carpenter (1987) failed to observe any aberration in niacin metabolism indicative of niacin deficiency resulting from excess leucine in chicks, rats and dogs. In view of these diverse observations, additional research is required to resolve this issue.

Qualitative improvement in the diet as a whole would be the right approach for prevention and control of any nutritional disorder in the population. However, such a blanket solution is not practicable considering economic and socio-cultural constraints. Based on the understanding of the factors that lead to pellagra in sorghum eaters, one of the alternative approaches to combating the disease would be identification of sorghum varieties with low leucine content and hence better leucine/isoleucine balance in the protein. Screening of sorghum varieties from a worldwide sorghum germplasm collection showed that genetic variability in protein content and lysine and leucine content of the protein is very large (Deosthale, Nagarajan and Visweswar Rao, 1972). Four varieties of sorghum (IS182, IS199, IS516 and IS4642) were identified as having a stable low-leucine character (leucine content below 11 g percent in the protein). Experiments in dogs have shown that animals fed sorghum proteins with less than 11 g percent leucine did not suffer from nicotinic acid deficiency (Belavady and Udayasekhara Rao, 1979). The four selected varieties are therefore considered safe and could be beneficially exploited to prevent pellagra in endemic areas (Deosthale, 1980).

Two Ethiopian sorghum varieties were identified for their high protein and high lysine content (Singh and Axtell, 1973a). Analysis of grain samples of those varieties when grown in India not only confirmed their high-protein, high-lysine character but also showed that their niacin content was about two to three times higher than that of normal sorghum grains (Pant, 1975). This observation indicates the second alternative approach to increasing the niacin content of the diet. Consumption of such varieties of sorghum may be expected to control and prevent pellagra even if the leucine/isoleucine balance is unfavourable.

FLUOROSIS, UROLITHIASIS AND OTHER TRACE-ELEMENT EFFECTS

High fluoride content of drinking-water is the most important factor in the aetiology of endemic fluorosis, but it is believed that diet and nutritional status is one of the factors that can influence the course of the disease (Pandit *et al.*, 1940; Siddiqui, 1955). In certain parts of India where fluorosis is endemic, the agroclimatic conditions are conducive for the cultivation of sorghum and millets and these foodgrains are the main staple in the diets of the population. In fluorotic areas of Andhra Pradesh, a clinical manifestation of bone deformation known as genu valgum was seen more frequently in subjects whose staple was sorghum (Krishnamachari and Krishnaswamy, 1974). Furthermore, it was observed that retention of fluoride was significantly higher on a sorghum diet than on rice (Lakshmaiah and Srikantia, 1977).

Several factors including trace-element nutrition have been implicated in the aetio-pathology of fluorosis and genu valgum. In this respect an observation of importance is that grain samples of sorghum and pearl millet grown in a fluorosis area had 60 percent more molybdenum than those from a non-fluorosis area (Deosthale, Krishnamachari and Belavady, 1977). Experiments in human subjects have shown that high intake of molybdenum affects copper metabolism (Deosthale and Gopalan, 1974). Moreover, in areas where the incidence of genu valgum was high, the copper content of water was found to be very low as compared to that in non-genu valgum areas (Krishnamachari, 1976); this perhaps indicates differences in the copper nutritional status of the populations in these areas. Both copper and

fluoride have a role in bone formation, and molybdenum promotes fluoride absorption (Underwood, 1971). However, no clear-cut evidence is available to explain the mechanism of this interrelationship with regard to the progression of the disease.

Urolithiasis, which is also endemic in certain parts of India, is a condition in which stones or calculi are formed in the urinary tract. This stone formation is said to be common in millet-eating populations (Patwardhan, 1961a). Several promoters and inhibitors of the lithogenic process have been implicated. There is some evidence to suggest that some trace elements are involved in the genesis of urinary calculi (Eusebio and Elliot, 1967; Satyanarayana *et al.*, 1988). Molybdenum, which is found in greater amounts in sorghum than in other foods, is an integral part of the xanthine oxidase system and is involved as such in the synthesis of uric acid, a component of urinary calculi. In studies conducted in human volunteers, however, dietary intake of molybdenum had no significant effect on uric acid excretion (Deosthale and Gopalan, 1974). Several trace elements have been identified in appreciable amounts in urinary calculi and kidney stones. The significance of their presence in relation to lithogenesis needs investigation.

O'Neill *et al.* (1982) observed that in parts of China, foxtail-millet bran contained very high amounts of silicon, up to 20 percent. High silicon from the soil accumulates in the bristles and is deposited in the grain pericarp. Consumption of this high-silicon foxtail millet has a role in the aetiology of oesophageal cancer in northern China.

MYCOTOXINS

Like other cereals, sorghum and millets are susceptible to fungal growth and mycotoxin production under certain environmental conditions. Mycotoxins not only threaten consumer health but also affect food quality, causing huge economic losses. To help developing countries improve their mycotoxin prevention and monitoring programmes FAO has published a manual on training in mycotoxin analysis (FAO, 1990a).

Storage fungi, mostly of the genera *Aspergillus* and *Penicillium*, are found on foodgrain stored with moisture content greater than 13 percent

(Sauer, 1988). Mouldy sorghum earheads were shown to be contaminated with aflatoxins B and G in India (Tripathi, 1973), in Uganda (Alpert *et al.*, 1971) and in the United States (Shotwell *et al.*, 1969). Aflatoxin has been shown to be hepatotoxic, carcinogenic, mutagenic and teratogenic. Proper drying and storage would greatly prevent the contamination of foodgrains. In India, infestation of pearl millet by a parasitic fungus, *Claviceps purpurea*, has caused an outbreak of ergotism, which is characterized by symptoms of nausea, vomiting, giddiness and somnolence (Patel, Boman and Dalal, 1958; Krishnamachari and Bhat, 1976).

A mouldy-grain toxicosis associated with consumption of sorghum grain was reported from Japan, and the causative fungus was *Fusarium* sp. (Saito and Ohtsubo, 1974). A strain of *Fusarium incarnatum* was isolated from naturally infested mouldy sorghum. The toxic metabolite present on mouldy sorghum grain infected with an isolated *Fusarium* strain was characterized for its chemical and biological properties. It was found to be T_2 toxin, 3α -hydroxy- $4\beta,15$ -diacetoxy- 8α -(3-methylbutyryloxy)-12,13 epoxy trichothecene.

Fusarium spp., primarily from infected millets, have been implicated in the aetiology of alimentary aleukia in humans in the former Soviet Union (Joffe, 1965).

INFESTATION

Insect damage during storage not only results in the loss of foodgrain but also affects its nutritional quality. Kapu, Balarabe and Udomah (1989) reported that crude protein values of all the foodstuffs including sorghum decreased significantly with insect damage. Pant and Susheela (1977) observed varietal differences in susceptibility to insect attack in 10 months' storage under ambient temperature and humidity. Moderate insect infestation did not alter the protein quality of the grain, but high infestation (30 percent) decreased it significantly. Insect-infested grain showed significant losses in total fat, mineral matter, thiamine and riboflavin. Sood and Kapoor (1992) have observed reduction in protein and starch digestibility on grain infestation in sorghum, wheat and maize. This effect was found to be dependent on the distribution of protein and starch in the kernel component

as well as on the feeding preferences of the insect. Infestation by the lesser grain borer, *Rhizopertha dominica*, an insect which feeds on endosperm, was found to reduce starch digestibility, while that by the khapra beetle, *Trogoderma granarium*, which attacks the germ, reduced the protein digestibility.

CONCLUSION

Several factors as discussed above affect the nutritional quality of sorghum and millets. Fortunately there are methods available to eliminate, inactivate or prevent the antinutritional and/or toxic principles that may be present naturally or because of contamination. Grain processing, discussed in Chapter 3, has a significant role.

Some recipes based on sorghum and millets

Method

1. Boil the flour with about 500 gms water.
2. Place it in a covered container and allow to ferment 24 hours before adding yeast. Once the yeast has an active fermentation process:
3. Add remaining water and add fermenting flour.
4. Cook for 10 to 15 minutes until smooth and thick.
5. Add sugar with the juice of 2 lemons, yeast and boil for another 2 minutes.
6. Add sugar and colouring of choice and boil again 2-3 times.

Note

A light colour cake, however, can be obtained by adding 100 gms of whole flour and 100 gms of jaggery. During boiling, add yeast to the flour to get a product with an excellent taste.

Ingredients

- 1 cup sorghum flour
- 1/2 cup water
- 1/2 cup yeast
- 1/2 cup sugar
- 1/2 cup jaggery
- 1/2 cup water to boil

UJI	Kenya
Thin porridge	United Republic of Tanzania Uganda

<i>Method</i>	<i>Ingredients</i>
<ol style="list-style-type: none"> 1. Mix the flour with about 1/2 cup water. 2. Place in a covered container and allow to ferment 24 to 48 hours in a warm place. Omit this step for an unfermented product. 3. Boil remaining water and add fermented flour to it. 4. Cook for 10 to 15 minutes until smooth and thick. 5. Add sour milk (or water or banana juice), stir and boil for another 2 minutes. 6. Add sugar and serve hot at breakfast or lunch. Serves 2-3. 	1 cup sorghum or millet flour 3-4 cups water 1 cup sour milk, water or banana juice 2 tablespoons sugar, or salt or lemon juice to taste
<i>Notes</i>	A light colour, smooth, flowing, creamy consistency and bland to sour taste and aroma are preferred. A dark, lumpy, grainy product with off flavour is not desired.

OGI

Thin porridge

Nigeria*Method*

1. Soak dehulled grains in cold water for 18 to 48 hours to soften and ferment the grains.
2. Wash the grains and ground to a coarse paste using a grinding stone.
3. Screen the slurry through muslin cloth and discard the bran and coarse particles remaining on the cloth.
4. Let the strained slurry stand for 5 to 6 hours and pour off the excess water, leaving just enough to cover the settled paste.
5. Bring water to boil.
6. Pour the paste in the boiling water (2 tablespoons for every 6 cups water) and stir vigorously until the paste gelatinizes.
7. Cover the bowl and cook for another 2 to 3 minutes.
8. Serve the thin, hot porridge as it is or add sugar or salt to taste.

Ingredients

Dehulled sorghum grains
 Water
 Sugar or salt to taste

Notes

The product should be light in colour, either white or creamy. Traditionally *ogi* is not stored. *Kafer*, *eko* or *ogide*, thicker versions of *ogi*, are stored. Change in flavour, texture or aroma is unacceptable.

ALKALI TÔ

Stiff porridge

Mali

Method

1. Boil about 4 litres water in a metal pot.
2. Mix 10 g wood ash in 650 ml water.
3. Add about 500 g sorghum flour and stir to form a homogeneous paste.
4. Swirl the paste in the boiling water.
5. Stir the boiling mixture about 8 minutes.
(Sometimes this mixture is consumed as thin porridge.)
6. Reduce the heat under the pot. Take out approximately one-third of the mixture and set it aside in a separate bowl.
7. Keep the mixture in the pot boiling and add, in small lots, the remaining sorghum flour.
8. After each addition beat the mixture vigorously with a flat wooden spoon. When the paste thickens too much to beat, add some of the thinner porridge that was kept aside. Again add flour and beat. Continue this cycle until all the flour and set-aside porridge are mixed in the boiling pot to form a homogeneous, thick paste.
9. Reduce heat, cover the pot and allow the paste to cook over low heat for about 12 minutes.
10. Remove the *tô* from the fire, cool for about an hour and serve.

Ingredients

1.25 kg dehulled sorghum flour
passed through 1 mm mesh
10 g wood ash extract

TUWO

Stiff porridge

Nigeria*Method*

1. Bring water to boil.
2. Prepare a paste of the flour in cold water.
3. Add the paste in small amounts to the boiling water and stir vigorously to prevent lump formation. For acid *tuwo* preparation cook the paste in water containing either lemon juice or tamarind pulp extract.
4. Cool the thick porridge.
5. Serve with vegetable sauce.

Ingredients

4 cups flour of whole or
dehulled sorghum or millet
9 cups water
Lemon juice or tamarind pulp
extract (optional)

Notes

A product prepared from dehulled grains is normally preferred. Whole-grain *tuwo* is tough, non-elastic and dark in colour.

BOGOBE

Stiff porridge

Botswana

Method

1. For fermented *bogobe* (*motogo-wa-ting* or *ting*), mix starter with dry sorghum meal.
2. Add 250 to 300 ml lukewarm water and stir to make a slurry.
3. Cover and allow to ferment for 24 hours.
4. Boil 1 500 ml water.
5. Add fermented meal to the boiling water. Stir frequently.
6. Cook for 12 to 15 minutes.

Non-fermented *bogobe* (*mosokwana*)

1. Boil about 1 litre water.
2. Add about 250 g sorghum meal to boiling water, stirring frequently.
3. Cook for 20 to 30 minutes.

Notes

Motogo-wa-ting is normally consumed with meat and vegetables in the morning and evening.

Mosokwana is generally eaten at lunch with meat and vegetables. *Bogobe* with medium to coarse texture is preferred. Dark colour of the product resulting from grain pigments is not acceptable.

Ingredients

- 300 g coarsely ground dehulled sorghum meal
 30 g starter (sorghum meal fermented in water for 48 hours)
 1 500 to 1 800 ml water

UGALI

Stiff porridge

Kenya

United Republic of Tanzania

Uganda

Method

1. Bring water to boil (in a clay pot).
2. Sprinkle a small amount of flour on the surface of the water. Continue heating.
3. As soon as water begins to boil again, add remaining flour in small amounts. Stir constantly to avoid lump formation.
4. Allow to cook for 2 minutes and remove about half of the hot slurry to another container.
5. Vigorously mix the remaining slurry in the pot using a wooden stick with a flattened cylindrical handle.
6. Add the set-aside slurry and continue boiling until the right consistency is obtained.
7. Continue cooking on a reduced fire for about 4 to 5 minutes.
8. Remove the *ugali* to a basket made for this purpose. The whole process of *ugali* preparation takes 15 to 20 minutes.
9. Serve with meat or vegetable sauce or stew, or green vegetables. Serves 2-3.

Ingredients

2-3 cups sorghum or millet flour
4-5 cups water

Notes

Ugali should be light in colour. It should not be sticky when eaten and should maintain the same characteristics in storage for 24 hours.

AMBALI

Stiff porridge

India

Method

1. Bring water to boil.
2. Mix the flour in cold water.
3. Add to the boiling water in small amounts.
4. Stir to prevent lump formation.
5. Cook until thick.
6. Leave overnight to ferment.
7. Add water or buttermilk. Mix well and serve.

Ingredients

- 1 litre water
 250 g sorghum or millet flour
 Salt to taste
 Buttermilk (optional)

Notes

A thin, soft, puréed meal made of sorghum flour or millet flour and buttermilk. After 24 hours of storage it should ferment to form buttermilk. It is served in a small quantity to each person.

SANKATI

Stiff porridge

India

Method

1. Sieve the flour through a 20-mesh sieve and separate grits from fine flour.
2. Boil water in a vessel.
3. Add grits to the boiling water while stirring.
4. Continue boiling and after 10 minutes gradually add the fine flour.
5. Continue stirring and cooking for another few minutes.
6. Pour the *sankati* on to a moist plate and prepare balls of approximately 10 cm diameter by hand.
7. Serve fresh with sauce, dhal, pickles, chutneys, buttermilk, curd, vegetable curries, etc. according to taste.

Ingredients

Coarsely ground whole-grain sorghum flour, winnowed and free of bran
Water

Notes

Sankati should be light in colour and slightly sweet in taste. It should not be sticky or pasty and should remain firm when stored in water.

ROTI

India

Unleavened thin flat bread

Method

1. Mix flour, water and salt to form a firm dough. Knead it thoroughly.
2. Shape it into a ball.
3. Sprinkle some dry flour on a wooden board and place the dough ball on it. Flatten the dough by hand, pressing into a circle of fairly even thickness.
4. Bake the flat dough on a hot shallow pan or grill. After about half a minute, sprinkle water on the baking dough.
5. Turn the *roti* over and bake it on the other side for 30 seconds or until it puffs.
6. Serve it with pickles, chutneys, dhal or vegetable sauces.

Ingredients

Whole-grain sorghum or pearl millet flour
 Water
 Salt to taste
 Oil (optional)

Notes

A thin, soft, light-coloured *roti* is preferred. For up to 24 hours of storage it should remain soft. A dark product is not desired.

TORTILLAS

Unfermented bread

Central America**Mexico***Method*

1. Prepare *masa* by mixing lime solution and sorghum grain in 3:1 proportion and cooking for 3 to 10 minutes at the boiling point.
2. Steep for at least 4 hours.
3. Prepare balls from the *masa* and press them into circles of about 15 cm diameter and 0.5 cm thickness.
4. Cook the tortillas on a grill or a traditional clay *comale*.
5. During cooking turn the tortilla once to brown it lightly on both sides.
6. Leave the cooked tortillas on the floor to cool a little, then keep them in a container lined with a cloth to cover.

Ingredients

Sorghum grain
0.5 percent lime solution

Notes

Sorghum tortillas are off coloured compared to those made with white maize. A tortilla prepared from a 1:1 mix of sorghum and maize is well accepted.

INJERA

Leavened round flat bread

Ethiopia*Method*

1. To prepare dough for 31 *injera* of 390 g each, sieve 4.5 kg sorghum flour into a large bowl.
2. Add 1 litre water and knead well by hand.
3. Stir in the *ersho* (starter).
4. Add more water and knead well.
5. Transfer the dough into a previously used *buhaka* (dough container). Cover and let stand for 48 hours.
6. Sift 1.6 kg flour into a large bowl to prepare a batter.
7. Heat 1.7 litres of water to boiling.
8. Pour the boiling water over the flour and mix well with a wooden spoon.
9. Let the mixed batter stand until it cools to approximately 55°C.
10. Add the batter to the fermented dough in the *buhaka*.
11. Add 2 litres water and mix well.
12. Let stand for about an hour until air bubbles form.
13. Heat a clay griddle (*metad*) over a fire half an hour before baking.
14. Grease the *metad* by sprinkling ground rapeseed over it and polishing with a folded piece of clean cloth. Dust away all the rapeseed. Grease in this way before baking each *injera*.

Ingredients

6.1 kg sorghum flour
 0.5 litre *ersho* (starter), a fermented thin yellowish fluid saved from previously fermented dough
 Water



15. Pour the batter on to the hot greased *metad* using a circular motion from outside towards the centre to make a circular *injera*. Use about 0.5 litre of batter for each *injera*.
16. When holes begin to form on the top of the *injera*, cover with the griddle lid (*akenbala*) and bake for 2 to 3 minutes.

Regional variations

Mixing cooked dough (*absit*) with fermented dough:

1. Ladle out about 800 g of the fermented dough.
2. Add 350 ml water and mix well.
3. Boil 750 ml water and stir in the above dough and water mixture.
4. Cook, stirring constantly, for 10 minutes.
5. Remove from heat. Cool to about 46°C.
6. Add the cooked dough to the fermented dough in the *buhaka*.
7. Mix well with a clean stick or a clean hand.
8. Add 2 litres water and mix well.
9. Let stand for about an hour to allow the batter to rise.
10. Bake as described before.

Fermenting together a mixture of three parts uncooked and one part previously cooked dough:

1. A few hours after the initial dough is mixed, take out one-fourth of the dough and cook it until it reaches the consistency of a porridge.



2. Mix the cooked dough thoroughly into the remaining initial dough.
3. Leave it overnight in the dough container.
4. Thin the dough with warm water and bake.

Notes

Injera is consumed with *wot*, a stew made from meat, pulse, vegetables or their combinations. Milk and milk products can also be served with *injera*. Desirable parameters include uniformly distributed "eyes" or perforations and a slightly sour flavour. A soft, thin, slightly moist and flexible product is accepted.

KISRA

Sudan

Thin pancake-type leavened bread

Method

1. In an earthenware container, mix flour, starter and enough water to form a paste.
2. Allow to ferment overnight, i.e. about 18 hours.
3. Thin dough to the consistency of a batter.
4. Spread about 100 ml of the batter on a hot iron plate, using a rectangular spatula (15 x 5 cm) to form a very thin layer.
5. Bake for about half a minute.
6. Remove and store in a container one on top of the other.
7. Cover with a cloth and store for use on the same or next day.
8. Serve with vegetables, legumes, meat stew or soup.

Ingredients

9 parts sorghum flour, generally white variety
 2 parts water
 1 part starter (yeast inoculum from a previously fermented batch of *kisra* batter)

Notes

A soft, thin, slightly moist and flexible product is preferred, with uniformly distributed "eyes" or perforations and a slightly sour taste.

SORGHUM OR MILLET "RICE"

India

Method

1. If using whole grain, soak it overnight in water and rinse it clean.
2. Boil or steam the dehulled or soaked whole grain until soft (20 to 40 minutes).
3. Serve hot with meat or vegetables.

Ingredients

- 1 volume dehulled or whole grain
3-4 volumes water

SORGHUM OR MILLET GRAINS WITH PULSE

India

Method

1. Bring water to boil.
2. Add pulse and boil until partially done.
3. Add sorghum or millet grain and continue boiling until tender.
4. Season as desired.
5. Serve hot with greens and lemon or orange slices.

Ingredients

2 cups whole or cracked grain
1 cup green gram dhal, peas,
beans, cowpeas or other pulse
7 cups water

PATE

Dehulled cracked grain

Nigeria

Method

1. Bring water to boil.
2. Add bean cake, onion, tomatoes, chilli peppers, salt and pepper.
3. Add coarsely ground grain.
4. Cook for 8 to 10 minutes.
5. Add spinach and continue cooking for another 2 minutes.
6. Serve hot.

Ingredients

- 4 cups coarsely ground whole or dehulled sorghum or millet grain
- 7 cups spinach
- 2 large chilli peppers (chopped)
- 6 medium-sized tomatoes
- 2 medium-sized locust bean cakes
- 1 onion

Notes

A sticky product with poorly defined grains is not desired.

KICHIDI

India

Method

1. Heat oil in a pot.
2. Add spices.
3. Fry onion and garlic.
4. Add water and boil.
5. Add dehusked millet, rice, soaked chickpea dhal, groundnuts and salt.
6. Cover and cook until done.
7. Serve hot, garnished with grated coconut and green coriander leaves.

Ingredients

- 2 cups dehusked sorghum or millet
1/2 cup rice
1/4 cup chickpea dhal soaked in water
1/2 cup groundnuts soaked in water
2 small onions
6 cloves garlic
50 g vegetable oil
2 teaspoons mixed spices: mustard, cumin, asafoetida and turmeric
Salt to taste

COUSCOUS**West Africa***Method*

1. Wet the finely ground flour with cold water and knead it until flour particles agglomerate.
2. Force the mixture through a fine screen (1.5 mm mesh).
3. Place the grains in a perforated pot fitted over another pot containing boiling water.
4. Put a cloth seal at the joint between the two pots. Heat the lower pot to steam the grains above for about 15 minutes. They will form a single large chunk.
5. Take out the chunk, break it into small aggregates and transfer them back to steam for another 15 minutes.
6. Remove the chunk, break it into aggregates and sift them through a sieve (2.5 mm).
7. Dry and store for future use.
8. To prepare *couscous* for serving, sprinkle cool water on the aggregates.
9. Mix thoroughly with fingers.
10. Mix the grains with ground baobab leaf powder and other ingredients such as peanut paste, okra, etc. and give it a final steaming for 15 minutes.
11. Allow it to cool slowly.
12. Serve with sauce or milk, or dry it and use as a convenience food.

Ingredients

Finely ground sorghum or millet flour

FURA

Snack preparation

Nigeria

Method

1. Mix flour, water and spices.
2. Prepare small round balls (2 to 3 cm in diameter).
3. Drop them into boiling water and cook for 30 minutes.
4. Pound cooked balls with water and spices until a smooth, elastic and cohesive lump is formed.
5. Again prepare small balls, rolling between the palms of the hand or on a wooden board dusted with dry flour.
6. Serve as it is or with *nono*, yoghurt or sour milk, as a snack.

Ingredients

- 4 cups millet or sorghum flour (sifted)
2 teaspoons hot spices
6 cups water
2 cups *nono* (fermented milk),
yoghurt or sour milk

POPPED SORGHUM

India

Method

1. Moisten the grains by sprinkling with water.
 2. Heat the grains in a covered pan over the fire.
 3. Serve the popped grains as a snack after sprinkling with salt and pepper.
 4. Other serving ideas: add some sugar syrup and butter and shape into balls; or serve with milk and a little sugar.

Ingredients

- ## Sorghum grain (popping variety)

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Sorghum and millets are the most important staple foods for millions of people in the semi-arid tropics of Asia and Africa. They grow in harsh environments where other crops do not grow well, and they sustain the lives of the poorest rural people. *Sorghum and millets in human nutrition* gives a broad overview of the history, nature, production, utilization, consumption, storage and processing of these foods. It provides extensive information on their nutritional value and chemical composition. In addition, antinutritional factors and ways of reducing toxic effects are discussed. The publication describes the preparation, nutritional composition and quality of various popular foods made from sorghum and millets. An annex gives many recipes from regions where sorghum and millets are important dietary staples. An extensive bibliography is included. *Sorghum and millets in human nutrition* will be of interest to nutritionists, food scientists, agronomists, extension workers, educators and others interested in these foods.

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